

NASA CR-134992

DESIGN OF SPACE-TYPE
ELECTRONIC POWER TRANSFORMERS

NOV. 1977

PREPARED BY

J. F. AHEARN AND J. C. LAGADINOS

MAGCAP ENGINEERING, INC.

222 BOLIVAR STREET

CANTON, MA 02021

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS RESEARCH CENTER

CLEVELAND, OHIO 44135

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FOREWORD

This report covers work performed by MagCap Engineering, Inc. for the National Aeronautics and Space Administration - Power Electronics Branch, Lewis Research Center, Cleveland, Ohio, under Contract NAS 3-17781.

The authors would like to thank the Lewis Research Center Project Manager for his technical direction and guidance during this program. In particular, the authors wish to acknowledge the technical suggestions and contributions made by the Project Manager, G. E. Schwarze, to Section 4.2 of this report.

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1.0 SUMMARY

1.1 Work Accomplished

A program was undertaken to obtain necessary information for the design and construction of electronic power transformers suitable for operation in the vacuum environment of space.

Areas of work carried on under the program included the following:

A. Transformer Design Trade-Off Studies

- 1) Open vs encapsulated construction
- 2) Effect of frequency
- 3) Skin effect
- 4) Selection of core materials
- 5) Temperature rise effects.

B. Experimental Program

- 1) Layer insulation for open transformers
- 2) Layer insulation for encapsulated transformers
- 3) Process of impregnation and encapsulation.

C. Temperature Rise Calculations

D. Design And Construction Of Specific Transformer Types.

E. Corona Tests On Open And Encapsulated Transformers.

1.2 Problem Areas

Areas of work in which unsolved or partially solved problems exist include the following:

A. Calculation And Verification Of Corona Inception Voltage Gradients In Open Transformers.

B. Corona Testing Of Transformers Under Operating Conditions

Present methods of corona testing in which full output voltage is applied to the shorted secondary are unrealistic in view of the fact that under operating conditions the secondary layers nearest to the primary do not normally see the maximum secondary output voltage.

C. Extension Of Upper Voltage Limits For Open Type Transformers.

D. Elimination Of Corona In The Area Of The Shield.

High voltage gradients exist at the edges of the copper foil customarily used for electrostatic shielding. Possible methods of reducing such voltage gradients include the use of insulating coatings and increasing the radius at the edge of the shield by crimping the foil or bonding to the foil edges a wire of relatively large radius.

E. Voltage Stress Design Criteria For Encapsulated Transformers.

F. Skin Effect For Non-Sinusoidal Voltage Forms.

G. Development Of Specific Core Loss And Exciting RMS Volt-Ampere Data For Non-Sinusoidal Excitation.

These data should be developed as functions of frequency, maximum flux density, temperature, core geometry, and lamination thickness.

1.3 Conclusions

- A. Corona free open type transformers having output voltages of 1.5 KV present no problems and indications are that output voltages of 3 to 5 KV are feasible with open construction. (See footnote.)
- B. Open and encapsulated space transformers with output of 1.1 KV at 2.62 KVA and efficiency of 98.5 % can be built with weight not exceeding 1 kilogram. Such transformers can be operated on a mounting surface maintained at 85 degrees C.
- C. Encapsulated space transformers with output voltage of 10 KV at 500 VA and efficiency of 97 % can be built with weight not exceeding 1.25 kilograms. Such transformers can be operated on a mounting surface maintained at 85 degrees C.
- D. Higher frequency operation can result in lower core and coil losses subject to the limitations imposed by skin effect in the conductors.
- E. Low loss ferrite cores afford lower losses than tape wound alloy cores currently available but the lower thermal conductivity of ferrites presents temperature rise problems which can be solved by the inclusion of thermally conducting strips of copper bonded to the ferrite.

Note: The term "corona free" as used in this report signifies that no corona is detectable using corona testing equipment with a sensitivity of 10 picocoulombs for a specimen having a capacitance of 500 picofarads or less. The applied voltage in testing should duplicate voltage stress conditions existing within the transformer at maximum operating voltage output.

- F. Calculation of voltage gradients can be a useful design tool for corona-free open transformers.

2.0 INTRODUCTION

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2.1 Objectives Of The Contract

The objectives of the contract may be stated as follows:

- 1) The design, construction, and testing of high reliability, low weight and high efficiency moderate and high voltage transformers for operation in the hard vacuum environment of space.

Output voltages and power of the contract transformers are:

1.1 KV at 2620 VA

10 KV at 500 VA

15 KV at 500 VA.

The investigation will include transformers of both the open and the encapsulated varieties, and a determination will be made of the advantages and limitations of the two types of construction in the ranges of power and voltage covered by the contract.

- 2) The preparation of a design guide incorporating necessary information on design methods, materials, and processing techniques to enable electronic engineers to construct transformers of high reliability and minimum weight suitable for long term operation in the space environment.

2.2 Transformer Specifications

Design requirements for the transformers are summarized in Table 1.

2.3 General Considerations

Transformers designed for operation in the environment of space must meet stringent requirements of high reliability, minimum size and weight, high efficiency, controlled temperature rise, and freedom from ionization, due to the necessity of unattended operation for long periods of time. Unlike earth-bound transformers, cooling of which is readily achieved by a combination of radiation and convection in air at atmospheric pressure, the mode of cooling of the space transformer is by conduction through the coil to the core and thence by means of mounting bracketry to a controlled heat sink. A relatively minor portion of the heat loss is transferred by radiation to surrounding objects or directly to space. Any voids or interfaces in the heat flow path under vacuum

TABLE 1. TRANSFORMER SPECIFICATIONS

GROUP I: MODERATE VOLTAGE TRANSFORMERS

TRANS- FORMER MODEL	TYPE OF CONSTRUCTION	INPUT VOLT- AGE	NO. OF PRIMA- RIES	NO. OF SECOND- ARIES	OUTPUT SEC. #1	VOLTAGE SEC. #2	OUTPUT SEC. #1	CURRENT SEC. #2	OUTPUT SEC. #1	POWER SEC. #2	MAX. MASS
O-M-2	OPEN	200 V	1	2	1.1 KV	1.0 KV	2.2 A	0.2 A	2.42 KVA	200 VA	1 Kg
E-M-2	ENCAPSULATED	200 V	1	2	1.1 KV	1.0 KV	2.2 A	0.2 A	2.42 KVA	200 VA	1 Kg

GROUP II: HIGH VOLTAGE TRANSFORMERS

TRANS- FORMER MODEL	TYPE OF CONSTRUCTION	INPUT VOLTAGE	TYPE OF PRIMARY	NO. OF SECOND- ARIES	VOLTAGE ACROSS EACH SECONDARY	TOTAL OUTPUT VOLTAGE	TOTAL OUTPUT POWER	MAX. MASS
O-S-10	OPEN	60	CENTER-TAPPED	1	10 KV	10 KV	500 VA	1.25 Kg
E-S-10	ENCAPSULATED	60	CENTER-TAPPED	1	10 KV	10 KV	500 VA	1.25 Kg
O-M-10	OPEN	60	CENTER-TAPPED	10	1 KV	10 KV	500 VA	1.25 Kg
E-M-10	ENCAPSULATED	60	CENTER-TAPPED	10	1 KV	10 KV	500 VA	1.25 Kg
O-S-15	OPEN	60	CENTER-TAPPED	1	15 KV	15 KV	500 VA	1.50 Kg
E-S-15	ENCAPSULATED	60	CENTER-TAPPED	1	15 KV	15 KV	500 VA	1.50 Kg

SPECIFICATIONS COMMON TO GROUP I AND GROUP II TRANSFORMERS

<u>DESCRIPTION</u>	<u>SPECIFICATION</u>
INPUT VOLTAGE WAVE FORM	SQUARE WAVE
FREQUENCY LIMITS	2 KHZ TO 40 KHZ
EFFICIENCY	97 PER CENT MINIMUM
AMBIENT TEMPERATURE RANGE	-55° C TO 85° C

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conditions will add disastrously to the thermal resistance and result in excessively high temperature rise.

To achieve high reliability it is mandatory to employ materials of construction which offer the maximum in thermal stability at the highest operating temperature, in order to ensure constancy of physical and electrical properties over the life of the system. Materials should exhibit minimum outgassing characteristics not only because of the degradation of properties that excessive outgassing signifies, but also because the release of gases in the intermediate pressure range between atmospheric and ultra-high vacuum can result in ionization or arc-over within the transformer or in adjacent components. Standards for maximum outgassing of space electronic materials have been established (Reference 1). Weight loss figures are provided by most resin vendors, and although these are not usually stated under vacuum conditions they provide a relative basis for the preliminary selection of suitable resins. Encapsulating resins and adhesives should exhibit satisfactory thermal shock properties as measured by the MIL-I-16923E test or by the more severe Olyphant washer test (Reference 2).

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The requirements of minimum weight, high efficiency, and controlled temperature rise are all tied in closely with the selection of suitable low loss core materials and with the designated operating frequency, subjects which are dealt with in Section 4. Nickel-iron-molybdenum alloys and certain ferrites now available make feasible the utilization of core materials at higher flux densities and higher frequencies than were practical using the older silicon steels. Certain combinations of flux density and frequency available to the designer can result in smaller core cross section area and lower turns, and therefore in lower copper losses and lighter weight of the transformer.

To meet controlled temperature rise requirements, special consideration has to be given to the thermal conductivity of materials used in transformer construction, and to the fact that any discontinuities in the heat flow path will offer significant impedance to heat flow under vacuum conditions. Since heat conduction through the core is a major mode of heat transfer in space transformers, the thermal conductivity of the core material is a major factor in temperature rise of the transformer.

Certain ferrites exhibit low specific core loss but have only a fraction of the thermal conductivity of the nickel-iron alloys. Also the losses of some ferrites are temperature sensitive. In order to maintain core temperature at a low level, it is expedient to incorporate copper laminations, one on either side of the core, to reduce the impedance of heat flow to the mounting bracket and heat sink. This arrangement may also be used advantageously with nickel-iron tape wound C-cores.

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A means of controlling temperature rise in the windings is to use a two coil construction with one coil mounted on each leg of the core. This reduces the number of layers of the winding through which the heat losses in the coil must flow, cuts the losses per coil by a factor of two, and distributes the coil losses over two halves of the core.

The requirement of freedom from ionization in theory should not be difficult to meet in the vacuum of outer space, since the absence of air molecules precludes ionization and voltage breakdown from this cause. The insulating materials used should possess negligible outgassing characteristics and should be of a sufficiently open structure to ensure that any gases evolved are expelled to space and do not accumulate within closed cells in the insulation system.

However, most space transformers are required to operate in air at atmospheric pressure for a period of time for pre-flight test purposes and hence the design criteria are those of a transformer operating in air. Transformers of open construction can be designed to operate corona free* at ratings up to 3 kilovolts without using excessive quantities of insulation or unreasonably large spacing between areas of high voltage gradient.

For higher voltages corona-free* operation in air is accomplished by impregnation and encapsulation of the coils, and in some instances the entire transformer is encapsulated. Effective impregnation requires the careful selection of insulating materials, resin, and process. A suitable insulation consists of alternate plies of film, e.g. polyimide, and a non-woven preferably oriented fibrous web (polyester or aramid) with the direction of orientation of the web parallel to the axis of the coil. Desirable properties

* See footnote on Page 2.

of the resin are low viscosity, low shrinkage on cure, low coefficient of expansion, and low temperature cure. Processing includes baking out of the coil to remove moisture, treatment under vacuum for several hours to remove occluded gases, introduction of the resin under vacuum, and then soaking of the coil in heated resin for a time sufficient to allow the liquid to impregnate the coil. Two part resins are degassed separately under vacuum to remove moisture and gasses, and after mixing are degassed again under vacuum. Long, slow cure at the lowest feasible temperature minimizes shrinkage of the resin during cure and upon subsequent cooling of the resin to room temperature.

Besides the open-to-space and resin encapsulated types of transformer construction, other options available to the transformer design engineer include gas-filled and liquid-filled types. Fluorinated gases such as sulphur hexafluoride and hexafluoroethane offer dielectric strength superior to air and stability at elevated temperature (Reference 3). Among dielectric liquids available are mineral oil, silicone oil, and fluorochemical liquids (Reference 4). Gas filled and liquid filled transformers require metal cases and insulating bushings, which add considerably to the weight and size of the unit. Both are vulnerable from the standpoint of leakage of the filling medium. Principally for these reasons, the preferred types of construction for space transformers are the open-to-space type for low voltage units and the resin-encapsulated type for either low or high voltage units.

2.4 References

References cited in the text appear in Appendix A.

2.5 Bibliography

A bibliography of pertinent articles from the literature is presented in Appendix B.

3.0 ELECTRONIC POWER TRANSFORMER DESIGN

The procedure to be described is adaptable to power transformers of low, moderate, and high voltage ratings of both open and encapsulated constructions.

The procedure involves the following steps:

- 1) Selection of core material
- 2) Preliminary calculation of core dimensions
- 3) Selection of insulating materials including magnet wire insulation, coil forms, layer and interwinding insulation
- 4) Coil design
 - 4.a) Calculation of wire size, number of turns and layers
 - 4.b) Establishment of margins
 - 4.c) Establishment of thickness of layer and interwinding insulation
- 5) Calculation of copper losses, core losses and efficiency
- 6) Calculation of temperature rise
- 7) Optimization of design with changes in core selection or coil design as may be necessary to meet specifications.

3.1 Selection of Core Material

The high efficiency and small size requirements of the contract transformers dictate the use of a low loss core material. Selection of a suitable core material is discussed in detail in Section 4.2.1.

3.2 Calculation of Power Handling Capability of Core

The voltage handling capability of a core is proportional to its cross section area, and the current handling capability to its window area. The product of the two areas, $A_c A_w$, is a measure of the power handling capability of the core.

The voltage capability of the core is determined from the basic transformer equation:

$$E_1 = 4(\text{FF}) B_m f A_c N_1 (\text{SF})_c \times 10^{-5} \quad (3.1)$$

where

E = RMS voltage of winding 1 (volts)

B_m = Maximum flux density (kilogauss)

A_c = cross sectional area of the core (cm^2)

N_1 = number of turns of winding 1

f = frequency (Hz)

(FF) = form factor = $\frac{\text{RMS voltage}}{\text{average voltage}}$

$(\text{SF})_c$ = space factor of core (i.e. fraction of A_c filled with magnetic material)

The current handling capability of the core window area for winding 1 is:

$$I_1 = \frac{(\text{SF})_{w1} J_1 A_{w1}}{N_1} \quad (3.2)$$

where

I_1 = RMS current flowing in winding 1 (amps)

J_1 = RMS inverse current density for winding 1 (cm^2/amp)

A_{w1} = Core window area occupied by winding 1 (cm^2)

$(\text{SF})_{w1}$ = fractional area of core window occupied by winding 1 conductor

Solving equation (3.2) for N_1 and substituting into equation (3.1) gives

$$A_c (\text{SF})_{w1} A_{w1} = \frac{E_1 I_1 J_1 \times 10^5}{4(\text{FF}) B_m f (\text{SF})_c} \quad (3.3)$$

For a transformer with n -windings ($n = 2, 3, \dots$), equation (3.3) is summed for all n -windings.

Letting

$$(\text{SF})_w A_w = \sum_{j=1}^n (\text{SF})_{wj} A_{wj}$$

the total $A_c A_w$ product then becomes

$$A_c A_w = \frac{(E_1 I_1 J_1 + E_2 I_2 J_2 + \dots + E_n I_n J_n) \times 10^5}{4 (FF) B_m f (SF)_c (SF)_w} \quad (3.4)$$

where

A_w = total core window area (cm^2)

$(SF)_w$ = Space factor for total window area (i.e., fraction of total window area filled with winding conductors)

If the inverse current density is identical for each winding so that

$$J_1 = J_2 = \dots = J_n = J$$

then equation (3.4) reduces to

$$A_c A_w = \frac{(E_1 I_1 + E_2 I_2 + \dots + E_n I_n) J \times 10^5}{4 (FF) B_m f (SF)_c (SF)_w} \quad (3.5)$$

Many vendors give $A_c A_w$ in terms of inches⁴. The conversion factor from cm^4 to inches⁴ is $\text{In.}^4 = \text{cm}^4 \times 0.0240$.

Two terms in equation (3.5), J and $(SF)_w$, require educated guesses on the part of the designer.

The transformer designer usually thinks of inverse current density, J , in terms of circular mils per ampere, because the cross-sectional area of wire is generally given in wire tables in circular mils. A good starting figure for preliminary design of small space transformers is 500 circular mils per ampere, but for multilayer windings this may have to be increased to 750 cir. mils/amp. or more to prevent excessive temperature rise. The conversion from cir. mils/amp to cm^2/amp is

$$\text{cir.mils/amp.} \times 5.067 \times 10^{-6} = \text{cm}^2/\text{amp.}$$

The coil space factor, $(SF)_w$, will depend on the size of the transformer and on the voltage rating. Higher voltages require larger margins and increased insulation thickness, and for small cores these will obviously occupy a larger fraction of total window area. Open-to-space transformers require more insulation than encapsulated transformers of a given voltage rating; therefore, the open-to-space transformer will have a lower coil space factor. The following are offered as rules of thumb for small transformers of the type with which we are concerned here:

Open transformer: $(SF)_w = 0.1$ to 0.2

Encapsulated transformer: $(SF)_w = 0.2$ to 0.4

These factors may be employed in the preliminary selection of a core, and are subject to revision after completion of the preliminary design.

3.3 Selection of Insulating Materials

The selection of insulating materials will be dependent on the type of construction elected. Trade-off between the open-to-space and encapsulated constructions are discussed in Section 4.1. Materials for the two structural types are listed in Sections 6.1 and 7.1, respectively.

3.4 Coil Design

3.4.1. Wire Size, Number of Turns, Number of Layers

The wire size for each winding is determined by the load current and the inverse current density for that winding.

Thus,

$$a = \frac{I}{J} \quad (3.6)$$

Where a is the cross sectional area of the conductor and is in cm^2 if J is cm^2/amp or is in cir. mils if J is in cir. mils/amp. Whether or not skin effect is appreciable for the calculated wire size should be determined by making references to Section 4.2.2.

The number of turns for each winding is found by solving equation (3.1) for N .

The number of layers required for each winding is determined by the ratio of the product of the number of turns and insulated wire diameter divided by the sum of the margins and winding traverse.

3.4.2. Margin Space

Margin space for open transformers is specified in accordance with creepage distances for open transformers given in Section 6.2, Table 24. For encapsulated transformers much higher stresses can be employed, and 50 volts per mil is considered conservative.

3.4.3. Thickness of Layer and Interwinding Insulation

Insulation thicknesses for open transformers are given in Table 25 of Section 6.2. For encapsulated transformers, these thicknesses may be reduced to the values given in Section 7.2.

3.5 Calculation of Copper Losses, Core Losses and Efficiency

The conductor loss or "copper loss" for each winding is

$$P_{cu} = I_L^2 R_w \quad (3.7)$$

where

P_{cu} = conductor loss (watts)

I_L = RMS load current (amps)

R_w = winding resistance (ohms)

The total conductor loss, (P_{cu}) total, is then the sum of the conductor losses for all of the windings.

The winding resistance, R_w , for each winding is

$$R_w = (MLT) N R_c \quad (3.8)$$

where

(MLT) = mean length of turn (ft)

N = number of turns

R_c = resistance (ohms) per foot

The value of R_c for a particular wire size is readily found in wire tables for a specific temperature T_1 . The value of R_c at any other temperature T_2 is found from the relation

$$\frac{R_c \text{ at } T_2}{R_c \text{ at } T_1} = \frac{234.5 + T_2}{234.5 + T_1} \quad (3.9)$$

where T_1 and T_2 are in degrees centigrade.

It should also be noted that the value of R_c given in the wire tables is the D C resistance. Under AC conditions the resistance of the winding can increase due to the skin and proximity effect. Whether or not a correction is necessary because of skin effect can be determined by referring to Section 4.2.2.

The mean length of turn for each winding wound on a coil form of inside dimensions L and W and thickness r is found with the aid of Figure 1. The notation used in the figure is defined as follows:

B_{ni} = inside build of n -th winding from exterior surface of coil form ($n = 1, 2, 3, \dots$).

B_{no} = outside build of n -th winding from exterior surface of coil form ($n = 1, 2, 3, \dots$).

P_i = inside perimeter of coil form.

P_o = outside perimeter of coil form.

P_{ni} = inside perimeter of n -th winding ($n = 1, 2, 3, \dots$).

P_{no} = outside perimeter of n -th winding ($n = 1, 2, 3, \dots$).

From Figure 1 it follows that

$$P_i = 2(L + W)$$

$$P_o = P_i + \frac{4(2\pi r)}{4} = 2(L + W) + 2\pi r$$

$$P_{ni} = P_o + \frac{4(2\pi B_{ni})}{4} = 2(L + W) + 2\pi(r + B_{ni})$$

$$P_{no} = P_o + \frac{4(2\pi B_{no})}{4} = 2(L + W) + 2\pi(r + B_{no})$$

The mean path length of the coil form is

$$(MLT)_o = \frac{P_i + P_o}{2} = 2(L + W) + \pi r \quad (3.10)$$

The mean length of any given winding is the arithmetical mean of the inside and outside perimeter of the given winding.

$$(MLT)_n = \frac{P_{ni} + P_{no}}{2} = 2(L + W) + 2\pi \left[r + \left(\frac{B_{ni} + B_{no}}{2} \right) \right] \quad (3.11)$$

$$n = 1, 2, 3, \dots$$

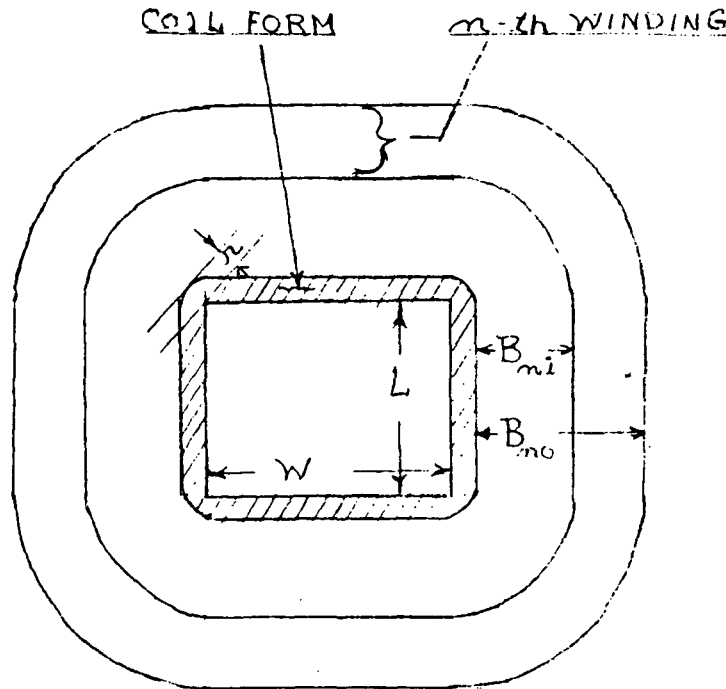


FIGURE 1
DIAGRAM USED IN THE DERIVATION OF THE
MEAN LENGTH OF TURN (MLT) OF THE m -th WINDING

The core loss, P_{core} , of the magnetic core is calculated from the product of the specific core loss (watts per unit weight or volume) and the weight (or volume) of the core. In Section 4.2.1., the effect of frequency and maximum flux density on the core loss is discussed.

The percent efficiency, η , of the transformer is calculated from the expression,

$$\eta = \left(\frac{P_{out}}{P_{out} + P_T} \right) \times 100 \quad (3.12)$$

where

P_{out} = output power (watts)

P_T = total loss = $(P_{cu})_{total} + P_{core}$ (watts)

3.6 Calculation Of Temperature Rise

The method used herein for the calculation of temperature rise is based on the assumption that heat generated by copper losses in the windings of the transformer is conducted inwardly to the core through a series of thermal resistances composed of magnet wire insulation, layer and interwinding insulation, the coil tube, and an interface between the coil tube and the core. Heat generated within the core is added to the copper loss and is conducted in the direction coinciding with the magnetic flux to the mounting brackets, through which it flows to a heat sink which is assumed to be maintained at a constant temperature. The overall temperature rise of the transformer is the difference in temperature between the outside layer of the winding and the heat sink. The hottest spot is therefore considered to be in the outside layer.

Heat radiated from the windings and exposed areas of the core and bracketry is neglected in the calculations since it is ordinarily a small fraction of the heat conducted, and the neglect of it leads to conservative values. It can, however, be calculated separately if the ambient temperature, or the temperature of objects in the line of view of the transformer is known.

The information required for the thermal analysis includes the copper and core losses of the transformer at an assumed operating temperature, the dimensions of the core, and comprehensive information regarding the design, such as wire size, winding width, number of layers, thickness and types of layer insulation. If preliminary calculations yield winding temperatures different from those assumed, a second calculation is performed using the necessary corrections.

Also required are the thermal conductivities of all materials of the transformer through which heat conduction occurs. Although these are temperature dependent, the variation over the operating range of the transformer is not great, and furthermore information regarding thermal conductivity as a function of temperature is not readily available. Since the thermal conductivity of non-metallic materials increases with temperature (Reference 10), the use of room temperature values for insulation leads to

a conservative result. A listing of thermal conductivities of some transformer materials is given in Table 2.

If the transformer is of a two-coil construction having two identical coils, the calculation is carried out on only one coil; if the coils are non-identical, a judgment is made regarding which coil represents the worst case, and the calculation is performed on that coil.

The procedure for calculating the coil ΔT 's will differ depending on the number of layers in a winding. If the winding consists of relatively few layers, the thermal resistances are calculated layer by layer using the dimensions and thermal conductivity of each layer of insulation. If a winding is composed of a large number of layers, it is more convenient to consider the coil as a mass of material uniformly heated by the I^2R losses in the copper, calculating the thermal resistance from the mean of the inside and outside surface areas of the coil and the thickness of insulation which comprises the coil. The copper is considered to have zero thermal resistance, a concept that is justified by the fact that the thermal conductivity of copper is 1000 to 2500 times that of the layer insulation.

The first step in the determination of the temperature rise is to calculate the essential coil dimensions which are:

1. Thickness of insulation
2. Length of heat flow path
3. Winding width
4. Mean length of insulation (MLI). This value is obtained in the same manner as the mean length of turn (MLT) and thus equation (3-11) is used to calculate (MLI).
5. Mean area perpendicular to the heat flow path. This mean area is the product of (3) and (4) above.

For example, a compilation of the above type of information is made in Table 28, for transformer OM 2 Sub 6 and in Table 35 for transformer OM 2 Sub 7.

TABLE 2
THERMAL CONDUCTIVITIES OF SOME SPACE TRANSFORMER MATERIALS

	Thermal Conductivity $\frac{(\text{watts} \times \text{in})}{(\text{in}^2 \times \text{deg. C})}$
Polyimide wire insulation (ML)	0.0037
Silicone rubber (RTV 60)	0.0079
Silicone rubber (Sylgard 183)	0.0080
Silicone rubber low volatile heat sink compound (C6-1102)	0.0106
Fiberglass board, silicone treated (G-7)	0.00835
Fiberglass board, polyimide treated (G-30)	0.00805
Polyimide film (Kapton H) 25 degrees C	0.00395
Polyimide film (Kapton H) 75 degrees C	0.00413
Mica paper-fiberglass, silicone bonded (3M 4350)	0.0017
Copper	9.7
Aluminum	5.5
Permalloy 80 metal	0.879
Permalloy 80, 1 mil stack, parallel to laminations	0.702
Permalloy 80, 1 mil stack, perpendicular to laminations	0.039
Permalloy 80, .625 in. stack, with 2 x .02 in. copper strips transverse to stack	
Parallel to laminations in direction of magnetic path (See notes on Table 26)	1.244
Perpendicular to laminations (See notes on Table 2)	0.620
Ferrite, MN-100	0.159
Ferrite, MN-100, .625 in. with 2 x .02 in. copper strips parallel heat flow (See notes on Table 2)	0.732
Filled epoxy, Scotchcast 251	0.0085

The second step in the determination of the temperature rise is to compute the thermal resistance, $(\Delta T/Q)$, from the heat flow path, λ , the thermal conductivity, K , and the mean area, A . Then, from the known heat input, Q , the temperature rise, ΔT , for that input and thermal resistance is calculated. The over-all temperature rise then is the sum of the ΔT 's. An illustration of this step is given in Table 29 for OM2 Sub 6 and in Table 36 for OM 2 Sub 7.

The thermal resistances are calculated for one coil from the outside layer to the core. At this point the heat losses are conducted in two parallel paths from the center of the core to the mounting brackets and the copper losses in the calculations are those of one-half of the coil. The core losses are those of one-fourth of the core for a two coil construction, or one-half of the core for single coil construction. The length of the heat path in the core is one-fourth of the total magnetic length for two coil construction or one-half of the total magnetic length for single coil construction.

It is not usually possible to add the thermal resistances, $\Delta T/Q$, and multiply by the total watts loss to obtain the over-all temperature rise, because in some instances the heat is introduced on one surface of the conducting member and removed from the opposite surface, while in other instances heat is generated within the material, added uniformly, or removed uniformly along the heat flow direction. In the first instance $\Delta T = \frac{Q\lambda}{KA}$, while in the latter three instances $\Delta T = \frac{Q\lambda}{2KA}$. An example of combined internal generation and uniform addition occurs in the conduction of heat from the center of the core under the winding to the section of the core at the outside edge of the winding. In this area losses from the winding are added uniformly along the length of the core and heat is generated internally within the core.

On other occasions, heat may be introduced at one end of the conducting member and removed at the other end, while additional heat is generated within the member. This occurs in the portion of the core external to the windings, where heat generated in the windings and in the portion of the core enclosed within the windings is conducted along the core to brackets

and heat sink, while the core losses external to the windings contribute additional self-generated heat. This situation can be treated by calculating the thermal resistance of the thermal path, $\frac{\Sigma}{KA}$, and using one-half the self generated heat plus all of the conducted heat in calculating ΔT .

The final step in the calculation of the over-all temperature rise is to re-calculate the individual ΔT 's until the operating temperature for the core and each winding agrees with the operating temperatures used to compute the individual heat inputs. This final step is an iteration process and the number of iterations performed depends on the accuracy desired. An illustration of this final step is given in Table 30 for OM2 Sub 6 and in Table 37 for OM 2 Sub 7.

NOTES ON TABLE 2

Calculation Of Thermal Conductivity Of Core Material With Added Copper Laminations (Parallel Heat Flow)

From the basic heat conduction equation,

$$Q = \frac{KA\Delta T}{x} \quad (3-13)$$

$$\text{or } K = \frac{Qx}{A\Delta T} \quad (3-14)$$

where

Q = heat conducted, (watts)

K = thermal conductivity, $\left(\frac{\text{watts} \times \text{in.}}{\text{in.}^2 \times \text{deg. C}} \right)$

A = area perpendicular to the direction of heat flow (in.^2)

ΔT = temperature difference along the heat flow path (deg. C)

x = length of heat flow path (in.)

For magnetic material or copper of width W and thickness t

$$A = Wt$$

and, from Equation (3-13),

$$Q = KtW \left(\frac{\Delta T}{x} \right)$$

Heat conducted by materials in parallel is additive. Therefore, using

subscripts 1 for magnetic material and 2 for copper, the total heat,

Q_T , is:

$$Q_T = Q_1 + Q_2 = K_1 t_1 W_1 \left(\frac{\Delta T}{x} \right)_1 + K_2 t_2 W_2 \left(\frac{\Delta T}{x} \right)_2$$

Since $W_1 = W_2 = W$ and at thermal equilibrium we assume that

$$\left(\frac{\Delta T}{x} \right)_1 = \left(\frac{\Delta T}{x} \right)_2 = \left(\frac{\Delta T}{x} \right)$$

then

$$Q_T = (K_1 t_1 + K_2 t_2) W \left(\frac{\Delta T}{x} \right)$$

Rearranging

$$\frac{Q_T X}{W \Delta T} = K_1 t_1 + K_2 t_2$$

Dividing through by $(t_1 + t_2)$

$$\frac{Q_T X}{W(t_1 + t_2) \Delta T} = \frac{K_1 t_1 + K_2 t_2}{t_1 + t_2} \quad (3.15)$$

The total cross-sectional area of the magnetic and copper material combination perpendicular to the direction of heat flow is,

$$A_T = W (t_1 + t_2)$$

Substituting A_T into equation (3-15) and comparing to equation (3-14) we have

$$\frac{Q_T X}{A_T \Delta T} = \frac{K_1 t_1 + K_2 t_2}{t_1 + t_2} = K_T \quad (3.16)$$

where K_T is the thermal conductivity of the combination.

Using the known values

$$K_1 \text{ (Permalloy 80)} = \frac{0.702 \text{ (watt in.)}}{\text{in.}^2 \text{ deg. C}}$$

$$K_2 \text{ (Copper)} = 9.7 \text{ " "}$$

the K_T of a 0.625 inch stack of Permalloy 80 in parallel with 2 x 0.02 inch laminations of copper is found to be by equation (3-16),

$$K_T = \frac{(0.702 \times 0.625) + (9.7 \times 0.04)}{(0.625 + 0.04)} = 1.244 \frac{\text{watt in.}}{\text{in.}^2 \text{ deg. C}}$$

The K_T so calculated applies to heat flow in the direction of the magnetic path, whether the copper strips are located parallel or transverse to the core laminations.

For heat flow perpendicular to the direction of the magnetic path, the thermal conductivity will depend on which of two possible directions is selected, and on the location of the copper strips either parallel with or transverse to the core laminations. For the present case, the copper strips are considered to be placed transverse to the core laminations. Heat flowing perpendicular to the laminations flows in two parallel paths, one of which

Notes on Table 2 (Cont.)

is through the copper and the other through the core across the stack.

K_T is then calculated as follows:

$$K_1 \text{ (Permalloy 80, 1 mil, across the stack)} = .039 \frac{\text{watts} \times \text{in.}}{\text{in.}^2 \times \text{deg. C}}$$

$$K_T = \frac{(0.039 \times 0.625) + 9.7 \times 0.04}{(0.625 + 0.04)} = 0.620 \frac{\text{watts} \times \text{in.}}{\text{in.}^2 \times \text{deg. C}}$$

3.7 Optimization Of The Design

The preliminary design is reviewed from the standpoint of voltage stresses, thermal gradients, utilization of copper and iron, and minimum size and weight. The final design is worked out incorporating any indicated changes that will optimize the design with respect to the operational requirements.

4.0 TRANSFORMER DESIGN TRADE-OFF STUDIES

In designing transformers for spacecraft applications a number of options are open to the designer with respect to various phases of the design such as type of construction, choice of insulating and core materials, and frequency of operation. In each instance it becomes necessary to weigh the advantages and disadvantages of several possible approaches and perform a trade-off study in an effort to arrive at the optimum transformer design for the given conditions of operation. The following sections will discuss trade-off considerations relative to the above subjects and present information to assist the transformer designer.

4.1 Open VS Encapsulated Construction

In the open-to-space construction, advantage is taken of the insulating properties of the ultra-high vacuum of space. Transformers built in accordance with this philosophy have operated successfully during the Sert II mission (References 5 and 6).

Coils are wound with high-temperature resistant materials (Class 180°C or higher), windings and terminations are secured with a high temperature adhesive, and no encapsulation or other type of enclosure is used. For mechanical reasons a varnish treatment may be employed using silicone or polyimide type varnishes to preserve the integrity of the windings.

A noteworthy advantage of the open type transformer is that materials for coil construction are available which exhibit minimal outgassing under high vacuum conditions and which are resistant to high temperature, with the result that degradation due to thermal causes is negligible. A further advantage is that any volatile degradation products resulting from long-term operation are constantly expelled to the space environment, so that no localized accumulation of such products can occur. In addition, problems of thermal shock resistance are largely eliminated.

Open type transformers are limited in maximum voltage ratings since these are normally required to operate for limited periods of time at atmospheric pressure during testing programs prior to flight. Therefore, designs must be based on corona and dielectric strength capabilities of the insulation system in air at sea level. Open transformers designed to operate at sea level will operate

successfully in the ultra-high vacuum of space provided that outgassing is not excessive. However, at certain intermediate altitudes air pressure may be such as to cause violent ionization which may be visible as a glow discharge. This will not happen if the maximum voltage between any two points is less than 300 peak volts which is the minimum ionizing voltage for an air gap of any length at standard atmosphere pressure.

The voltage limitations of open type transformers are set by the relatively low breakdown levels of unimpregnated insulation systems tested in air. Figure 2 presents plots of experimental corona data obtained on Kapton H film and Nomex paper of various thicknesses used as layer insulation between windings of a coil. It is seen that .05 inches (50 mils) affords corona protection up to about 3000 volts. The shape of the curve indicates that further increase in insulation thickness would yield only minor improvement in corona inception voltage. Corona voltages for various creep distances between adjacent windings are shown in Figure 3. It will be noted that wire size is a factor influencing corona inception voltage under these conditions, especially at small creep distances. At least 1/4 inch creep distance is required to prevent corona at 5000 volts, for Number 30 wire.

From the data in the curves of Figures 2 and 3 it is evident that space factors (ratio of conductor area to core window area) of open construction high voltage windings will be relatively low and will be dependent on the size and geometry of the core. For large cores, the relative window area occupied by margins and insulation will be lower, and the space factor higher, than for small cores. For rectangular core windows, if the window width is large compared to the window height, relatively less area will be assigned to coil margins, thus resulting in better space factor than in the case of a core having window width smaller than the window height.

It is difficult to assign an arbitrary maximum voltage capability to the open construction transformer without considering specific design requirements; however, for small space transformers, 3 KV appears to be quite feasible and in some instances this could probably be extended to 5 KV.

Another limitation of the open-to-space transformer lies in its reduced ability to conduct heat losses occurring in the windings due to the lower thermal conductivity of the insulation system which includes numerous voids. The

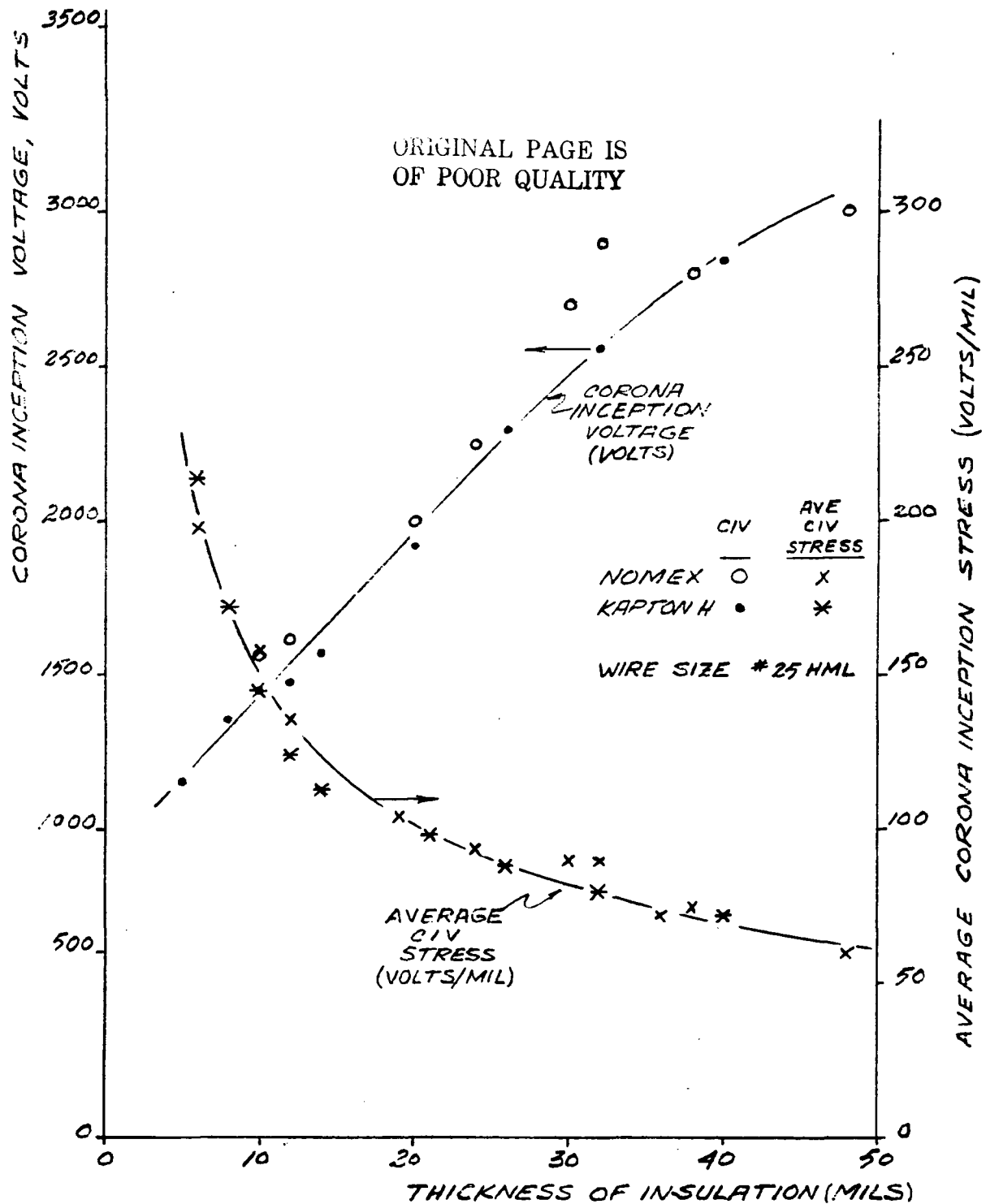


FIGURE 2
CORONA INCEPTION VOLTAGES AND AVERAGE CIV STRESSES
FOR UNIMPREGNATED NOMEX 40 AND KAPTON H FILM

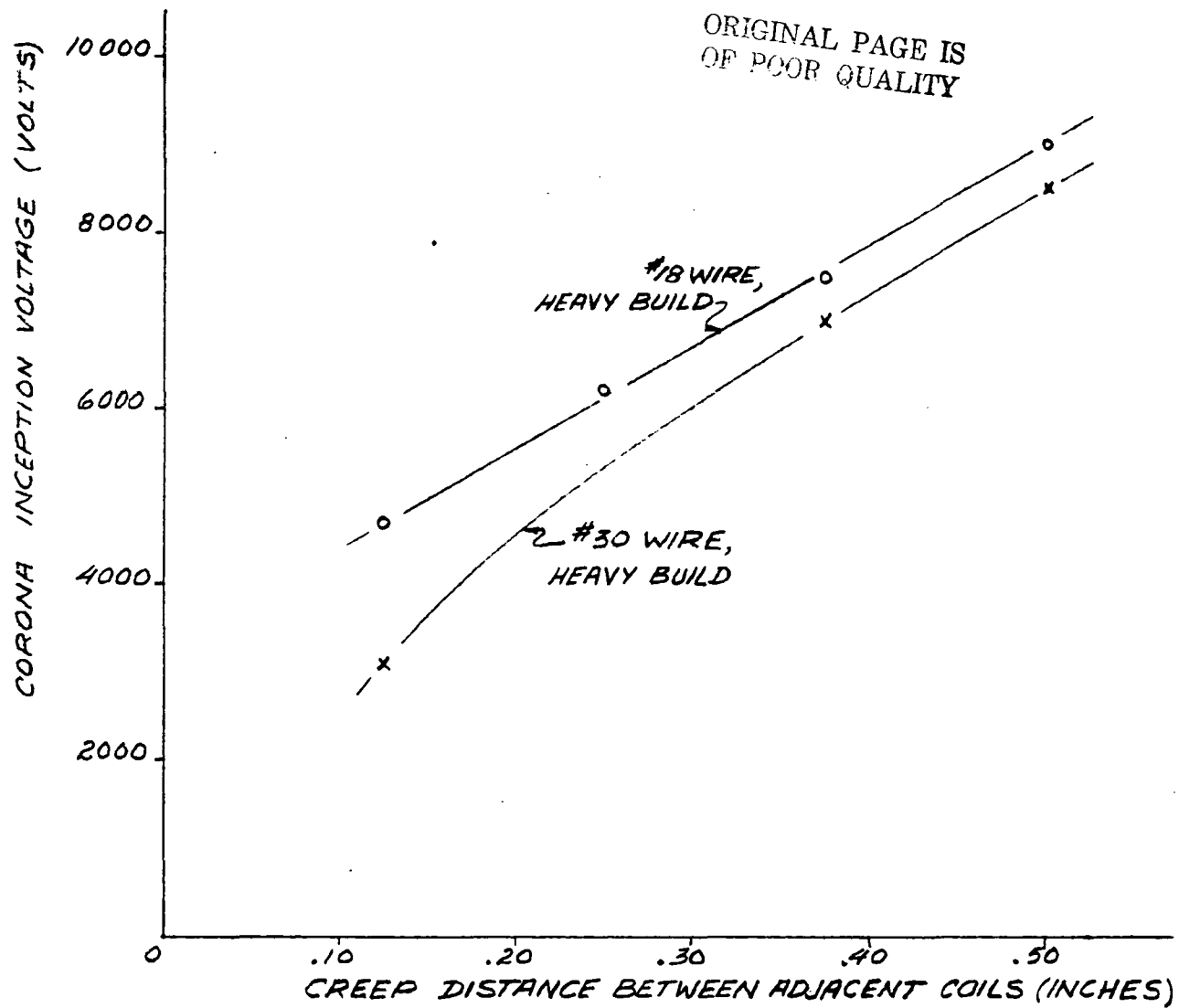


FIGURE 3

CORONA INCEPTION VOLTAGE VS. CREEP DISTANCE
FOR OPEN TYPE COILS IN AIR

relative importance of this limitation will vary from one transformer to another, depending on the magnitude of the heat losses to be conducted, and on the fraction of the temperature gradient in the coil referred to the overall temperature rise from heat sink to hottest spot. Certain interfaces, for example those existing between the coil tube and the core can be filled with heat conducting material to reduce the temperature gradient in this area. Judicious use of heat conducting members of aluminum or copper in parallel with the core can reduce further the overall temperature rise. Using such expedients, satisfactory power handling capabilities can be designed into the open type unit.

Details of the construction of open-to-space transformers are presented in Section 6 of this report.

The encapsulated construction offers advantages of higher voltage capability, improved heat transfer, and environmental protection during sea level testing.

To maximize the high voltage advantage, the coil is impregnated with a resin having suitable viscosity and flow characteristics that ensure complete penetration into the winding, filling all existing voids. The cured resin should be sufficiently flexible to prevent cracking and void formation during thermal cycling. Low weight loss under high vacuum is not necessarily a requirement if the impregnated coil is subsequently encapsulated in another resin exhibiting satisfactorily low weight loss. Ideally, the resin used should be of a high temperature class (180°C or better) to minimize both thermal degradation and the production of volatile materials under operating conditions. Resins which combine the properties of low viscosity and flexibility do not appear to be presently available for the 180 degrees C temperature class. However, suitable epoxies of the 155 degree C class are available.

Encapsulated coils suffer from a number of disadvantages. High corona inception voltages are achieved only by the selection of suitable layer and barrier insulations of a sufficiently open construction to ensure thorough impregnation by the resin, and by careful processing techniques. Best thermal shock resistance is exhibited by flexible or semi-flexible filled compounds, but these generally have relatively high weight loss due to the presence of low molecular weight materials in the formulation.

Two alternative methods of encapsulation have been investigated in the program. In the first method, the coil is impregnated under vacuum with a low viscosity flexible or semiflexible resin and subsequently encapsulated in a rigid resin exhibiting low weight loss under vacuum conditions. The impregnant has relatively high weight loss but volatile constituents are effectively sealed in by the external encapsulating medium. The second method employs a low viscosity low weight loss filled epoxy as both impregnating and encapsulating medium.

Tests conducted under the program using room temperature cured polyurethane elastomers as the preimpregnating resin gave satisfactory initial CIV levels, but on temperature cycling between 25 and 100 degrees C, considerable degradation of the CIV occurred, probably due to a post-curing of the polyurethane resin. Further investigation showed that high CIV's which remained stable after thermal cycling could be achieved in a single stage process by using a low viscosity, low weight loss filled epoxy (3M Company Scotchcast 251). This resin has moderately good thermal shock resistance and passes the MIL-I-16923E Test from -55 to 105 degrees C. While it is considered adequate for transformers of small size, such as those specified in this contract, for larger castings it may prove necessary to employ a more flexible compound with some sacrifice of weight loss.

The data in Table 3 illustrate the higher voltage capability of windings impregnated and cast in Scotchcast 251 compared with unimpregnated windings; the average CIV stress of the impregnated coils is from 3 to 6 times that of the untreated coils, with the greatest improvement occurring in the thinner insulations. A significant reduction in core window area, and therefore in overall size of core, is therefore achieved by impregnation and encapsulation.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3

Average Corona Inception Stress Of Coils Impregnated And
Cast In Scotchcast 251 Compared With Untreated Coils

Wire #25 HML

Insulation: Interleaved .002 Kapton-H and .0012 Polyester Web

Insulation Thickness (Mils)	Average CIV Stress (Volts/Mil)	
	Impregnated Coil	Untreated Coil
3.2	1550	240
6.4	1090	190
9.6	835	155
24.8	387	90
32.0	263	80

4.2 Effect Of Frequency

By rearranging the transformer equation, (Equation 3.1), in the form,

$$\frac{E \times 10^5}{4(\text{FF})(\text{SF})_c} = (B_m f) (N A_c) \quad (4.1)$$

it is seen that for a given E , (FF) , and $(\text{SF})_c$, that

$$\frac{E \times 10^5}{4(\text{FF})(\text{SF})_c} = C \quad (4.2)$$

where C is a constant. It follows then that

$$(B_m f) (N A_c) = C \quad (4.3)$$

From Equation 4.3 it is seen that as the $(B_m f)$ product increases, the $(N A_c)$ product must decrease proportionately. This decrease in the $(N A_c)$ product can be accomplished in one of five ways:

- 1) Decrease N and keep A_c constant
- 2) Decrease A_c and keep N constant
- 3) Decrease both N and A_c
- 4) Decrease N and increase A_c but rate of decrease in N is greater than rate of increase in A_c to give a decrease in $(N A_c)$
- 5) Decrease A_c and increase N but rate of decrease in A_c is greater than rate of increase in N to give a decrease in $(N A_c)$

In like manner the $(B_m f)$ product can be increased by one of five ways:

- 1) Increase B_m and keep f constant
- 2) Increase f and keep B_m constant
- 3) Increase both f and B_m
- 4) Increase B_m and decrease f but rate of increase in B_m is greater than rate of decrease in f to give an increase in $(B_m f)$
- 5) Increase f and decrease B_m but rate of increase in f is greater than rate of decrease in B_m to give an increase in $(B_m f)$.

If the $(B_m f)$ product is increased by an increase in B_m it should be noted that B_m cannot exceed the saturation flux density, B_s , of the core material. If the increase in the $(B_m f)$ product is obtained by an increase in the frequency, f , then the skin effect in the winding conductors can begin to play a dominant role so that the DC resistance must be replaced by the AC resistance of the winding. The skin effect in conductors is discussed in Section 4.2.2.

The relationship between the $(B_m f)$ product and the specific core loss will be investigated in Section 4.2.1.

As noted above, a decrease in the $(N A_c)$ product can be accomplished in one of five ways. We now investigate what this decrease does in terms of the transformer's loss and weight. A decrease in the number of turns N decreases the length of winding conductor so that both the conductor weight and DC resistance decrease. A subsequent decrease in the Joule loss ($I^2 R$ loss) results due to the decrease in DC resistance. Thus, a decrease in N leads to a decrease in both the transformer's weight and loss.

A decrease in the core cross-sectional area, A_c , causes a decrease in the conductor mean length of turn (MLT). Again, the length of winding decreases giving a decrease in the conductor weight and DC resistance and a resultant decrease in the $I^2 R$ loss. A decrease in A_c can also lead to a lower core loss providing the specific core loss of the core material does not increase as the $(B_m f)$ product increases. The core loss is the product of the specific core loss (watts/lb.) times the weight (lbs.) of the magnetic core material. The weight of the core is proportional to the core volume which is proportional to A_c . Thus, as A_c decreases, the core volume decreases which cause a decrease in both the core weight and core loss. Thus, a decrease in A_c leads to a decrease in the transformer's weight and loss.

The effect on the transformer's loss and weight when N increases and A_c decreases, or when N decreases and A_c increases to give a resultant decrease in the $(N A_c)$ product would require a detailed analysis beyond the scope of this study.

4.2.1 Effect Of Frequency, Flux Density, And $(B_m f)$ Product On Core Loss

The specific core loss of a magnetic core material is found to be dependent on the maximum flux density, frequency, excitation waveform, temperature, core geometry, and lamination thickness. A general mathematical expression relating the above independent variables to the specific core loss has been and continues to be an area of investigation. Present mathematical relations are limited in application since they cannot be applied with success to all the available core materials operating under a wide range of conditions.

The specific core loss, SCL, of a magnetic material is usually characterized graphically either by (1), plotting specific core loss, SCL, against maximum flux density, B_m , with frequency, f , as the parameter, or (2), plotting specific core loss, SCL, against frequency, f , with maximum flux density, B_m , as the parameter. In both cases the excitation waveform, temperature, core geometry, and lamination thickness are held fixed for a given plot.

A new way used in this study to graphically characterize the specific core loss is to plot the specific core loss, SCL, against the $(B_m f)$ product. The information contained in this type of plot is similar to that available in the two plots described above, but it is found that this new type of plot provides additional insight for analysis purposes. Indeed, this new type of plot for various core materials and core geometries should by itself allow the transformer designer to perform specific core loss trade-off studies.

Among the core materials investigated for this program, two were found to have satisfactory specific core loss properties up to the contract upper frequency specification of 40 KHz. The first of these materials is Permalloy 80, an iron-nickel-molybdenum (16:80:04) alloy manufactured by Magnetics, Inc. The second material is MN-100, a ferrite, manufactured by Ceramic Magnetics. The selection of these two materials for use in the final transformer designs should not be construed as an endorsement of these two materials. Core materials similar to the above materials and available from other manufacturers should give satisfactory results. The above two materials will be used for a discussion and analysis of the specific core loss in terms of frequency, maximum flux density, and the $(B_m f)$ product.

Figures 4, 5, 6, and 7 are plots of specific core loss for a 0.001 inch thick laminated C-core of Permalloy 80 material run under sine wave voltage excitation and room temperature conditions. Figure 4 is a plot of specific core loss vs maximum flux density with frequency as the parameter. Figure 5 is a plot of specific core loss vs frequency with maximum flux density as the parameter. Both Figures 6 and 7 are a plot of specific core loss vs the $(B_m f)$ product with frequency as the parameter. Figure 6 is plotted on linear scale paper, while Figure 7 is plotted on semi-logarithmic paper. From Figure 6 it is clearly seen that the specific core loss is not a linear function of the $(B_m f)$ product while by Equation 3.1, if all variables are held constant except E ,

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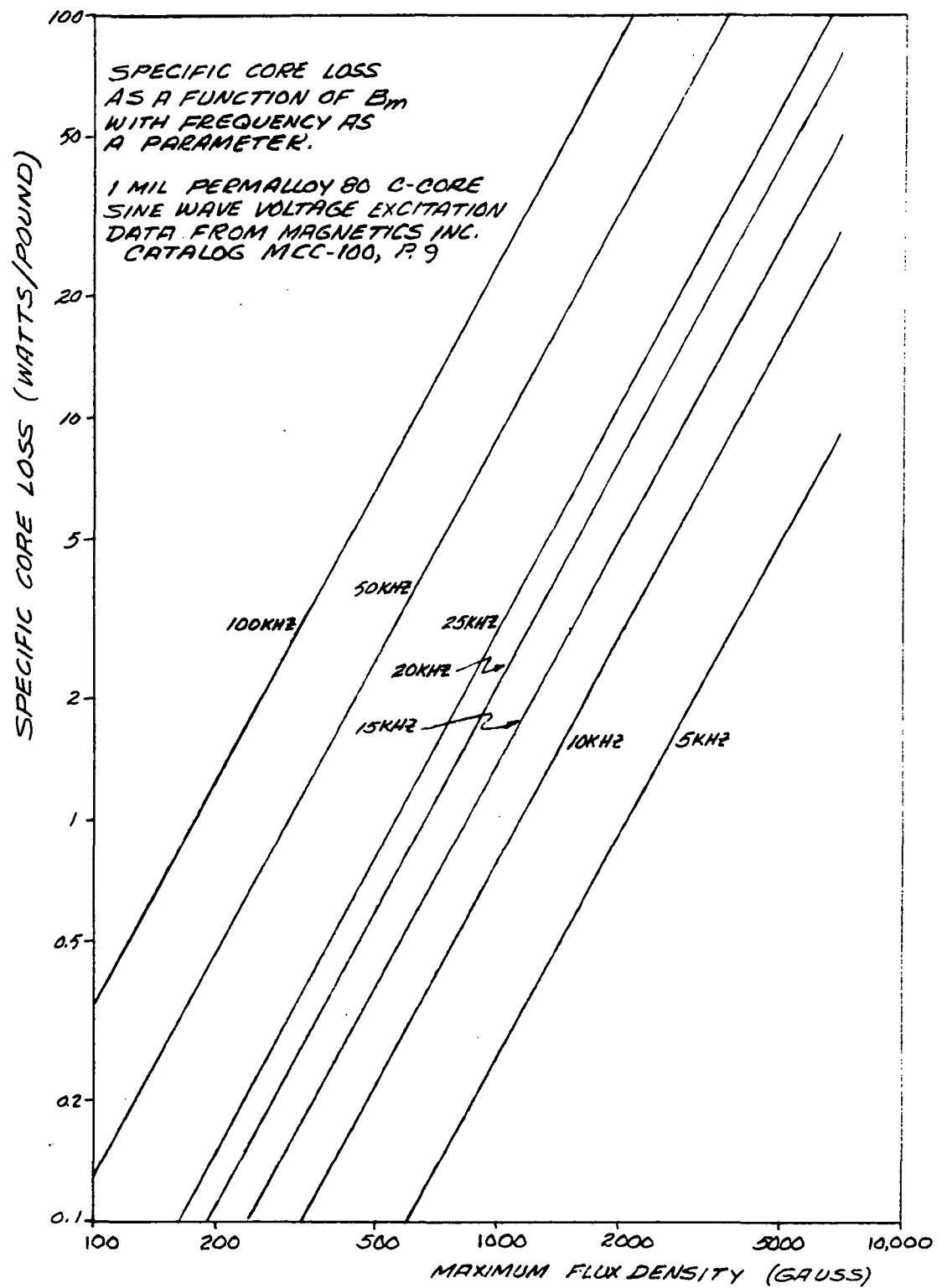


FIGURE 4

SPECIFIC CORE LOSS VS. B_m , FREQUENCY A PARAMETER

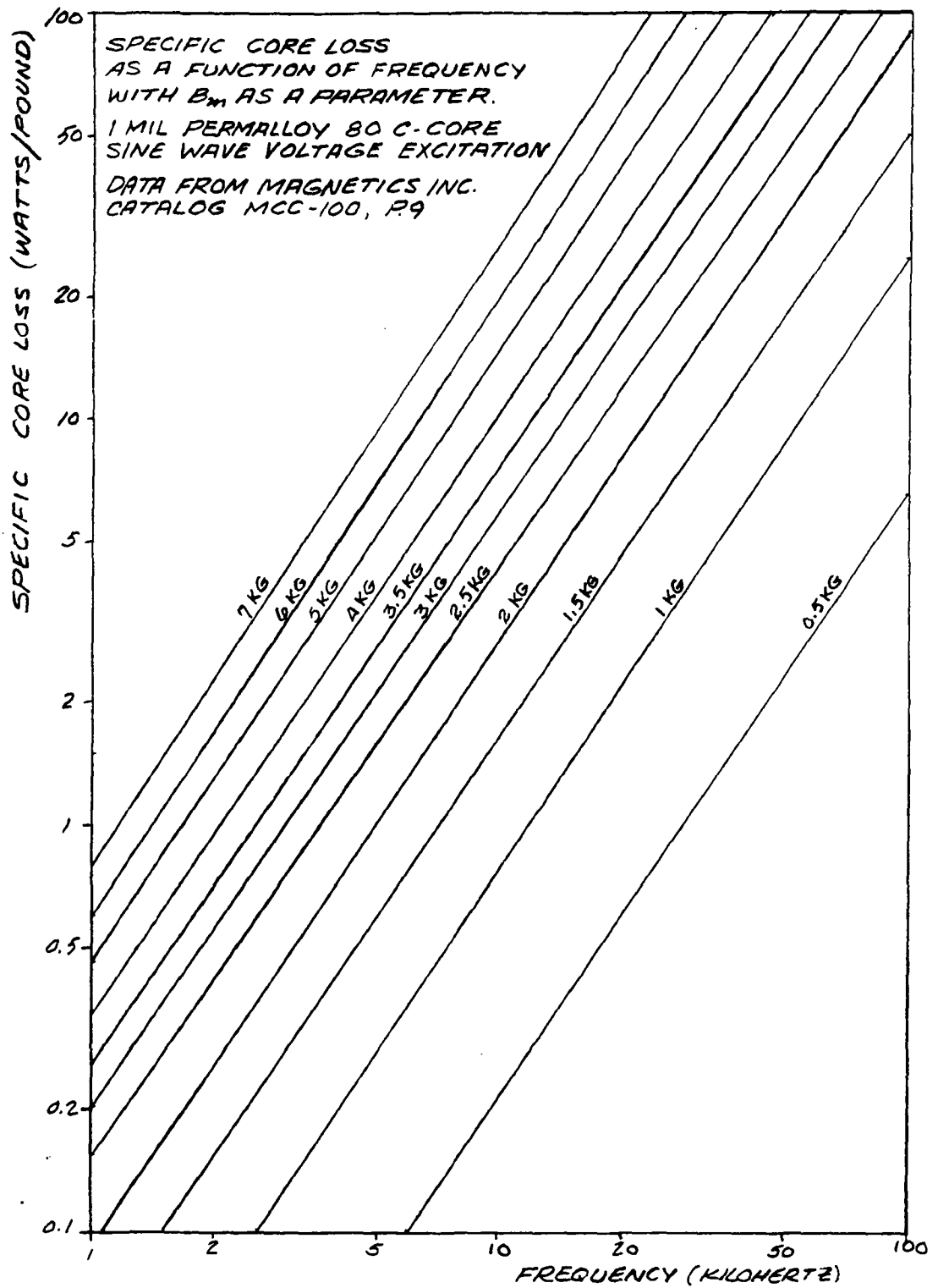


FIGURE 4

SPECIFIC CORE LOSS VS. FREQUENCY, B_m A PARAMETER

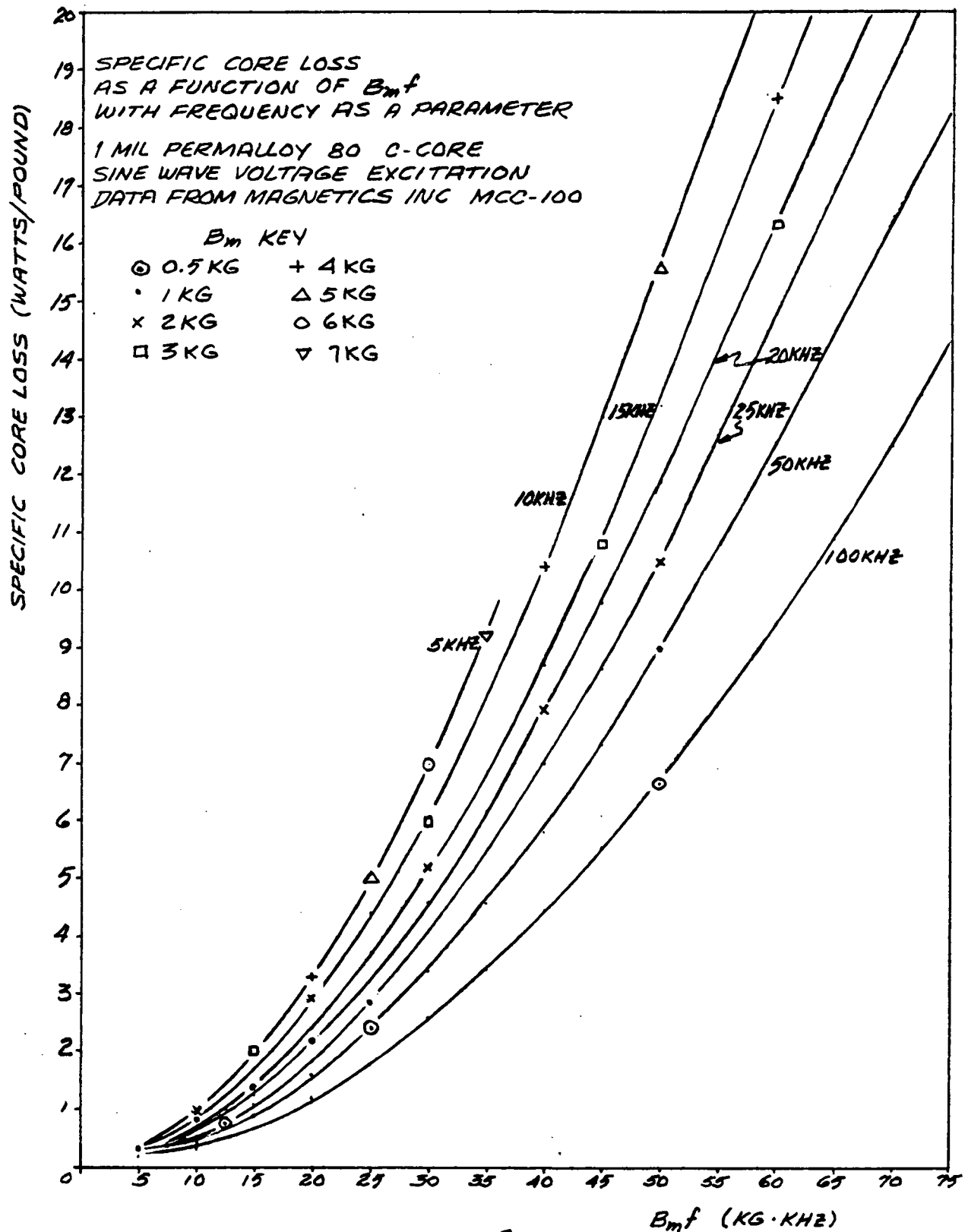


FIGURE 6
SPECIFIC CORE LOSS VS. $B_m f$, FREQUENCY A PARAMETER

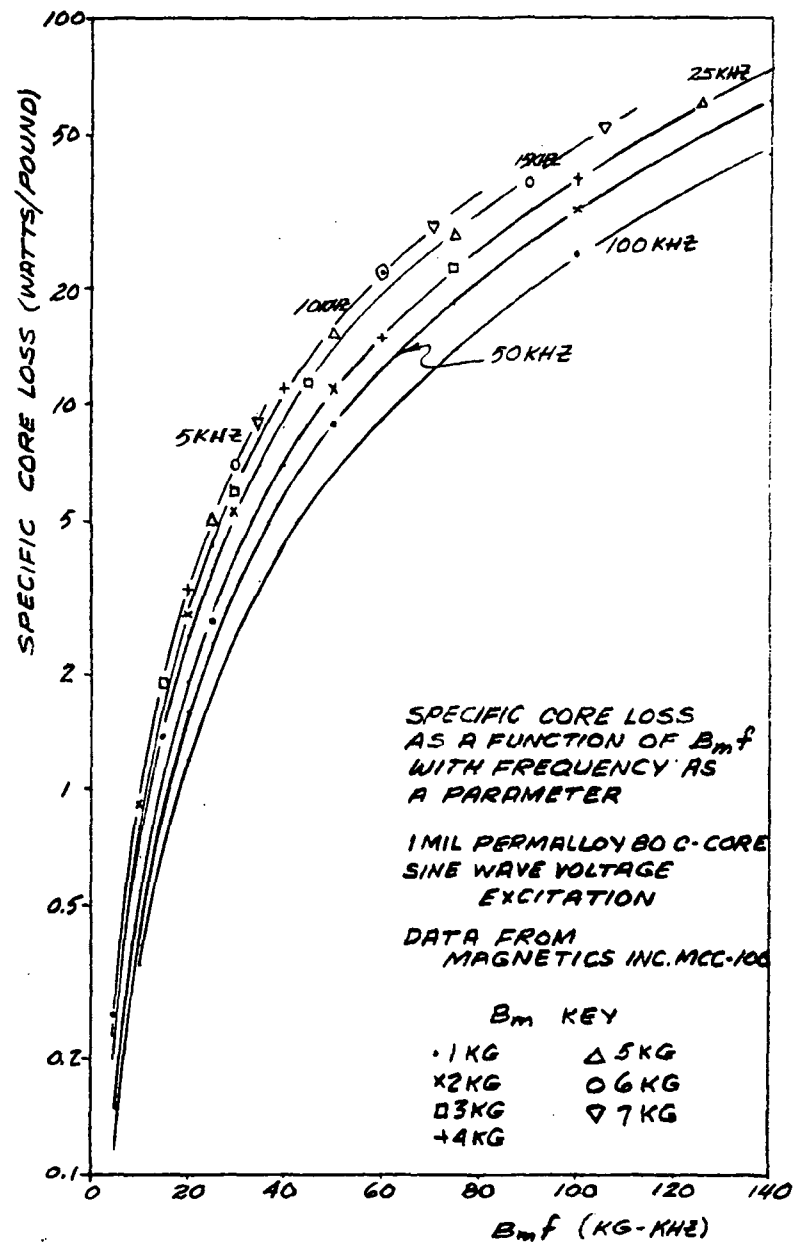


FIGURE 7
SPECIFIC CORE LOSS VS. $B_m f$, FREQUENCY A PARAMETER

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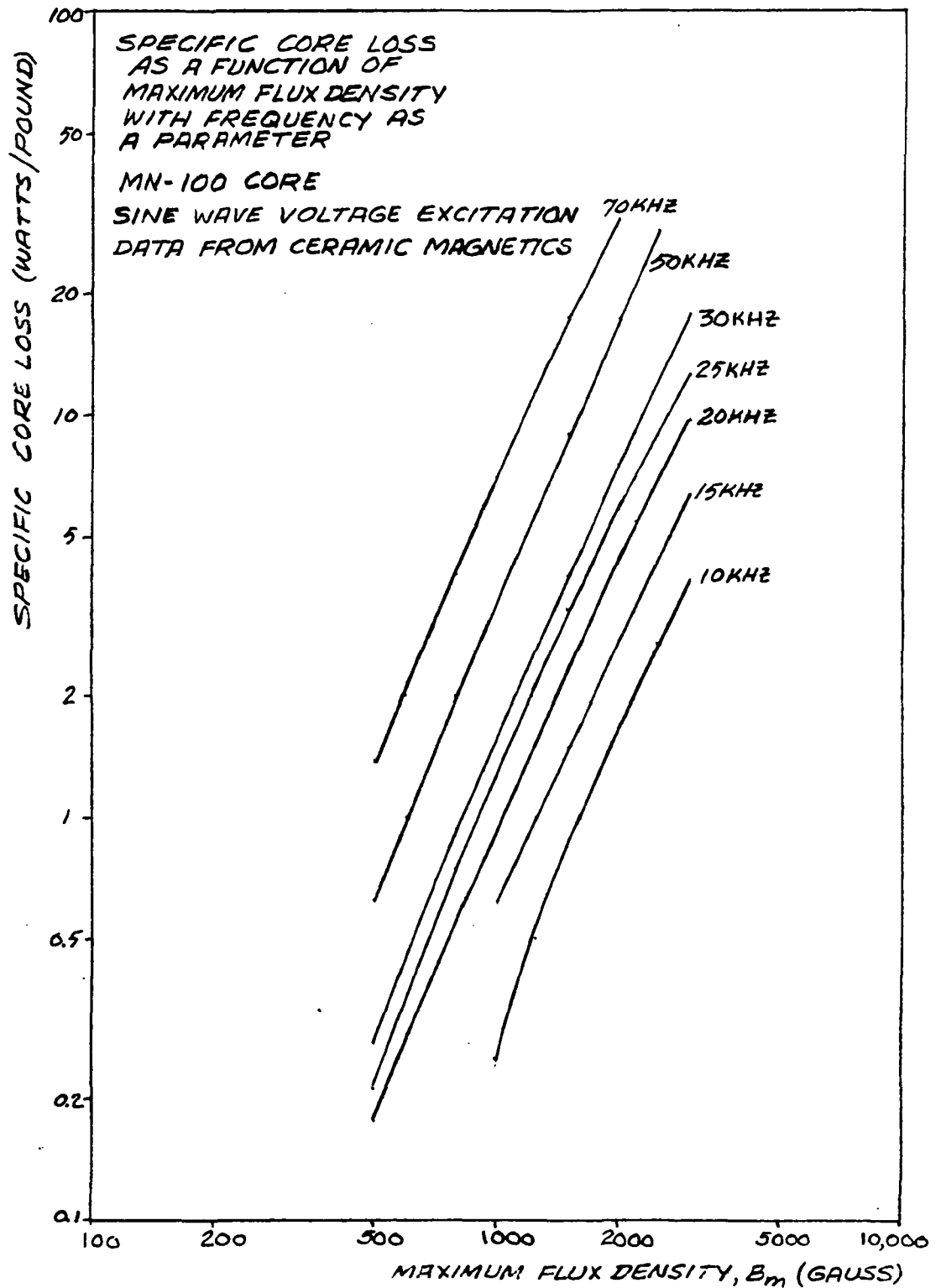


FIGURE 8

SPECIFIC CORE LOSS VS. B_m , FREQUENCY A PARAMETER

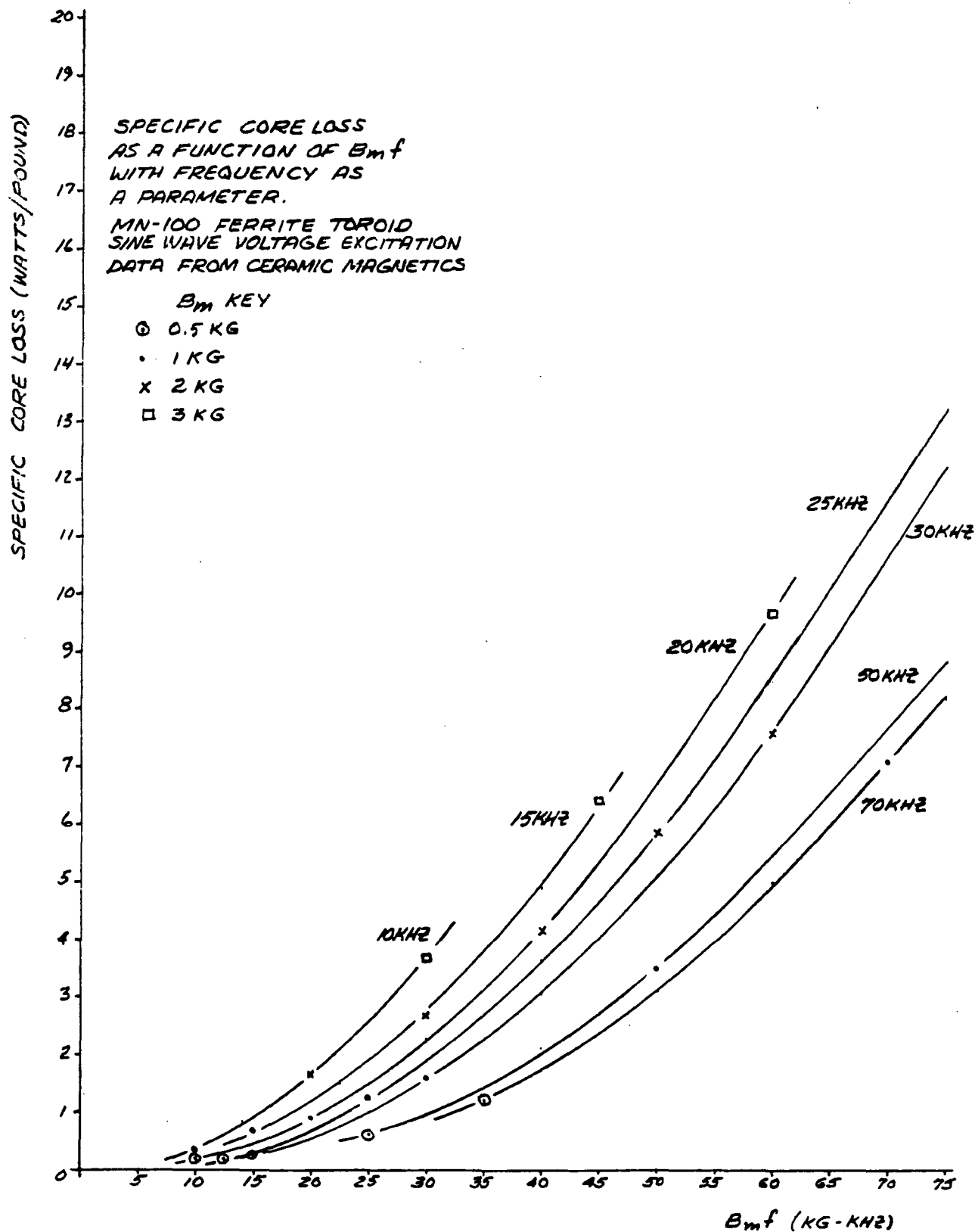
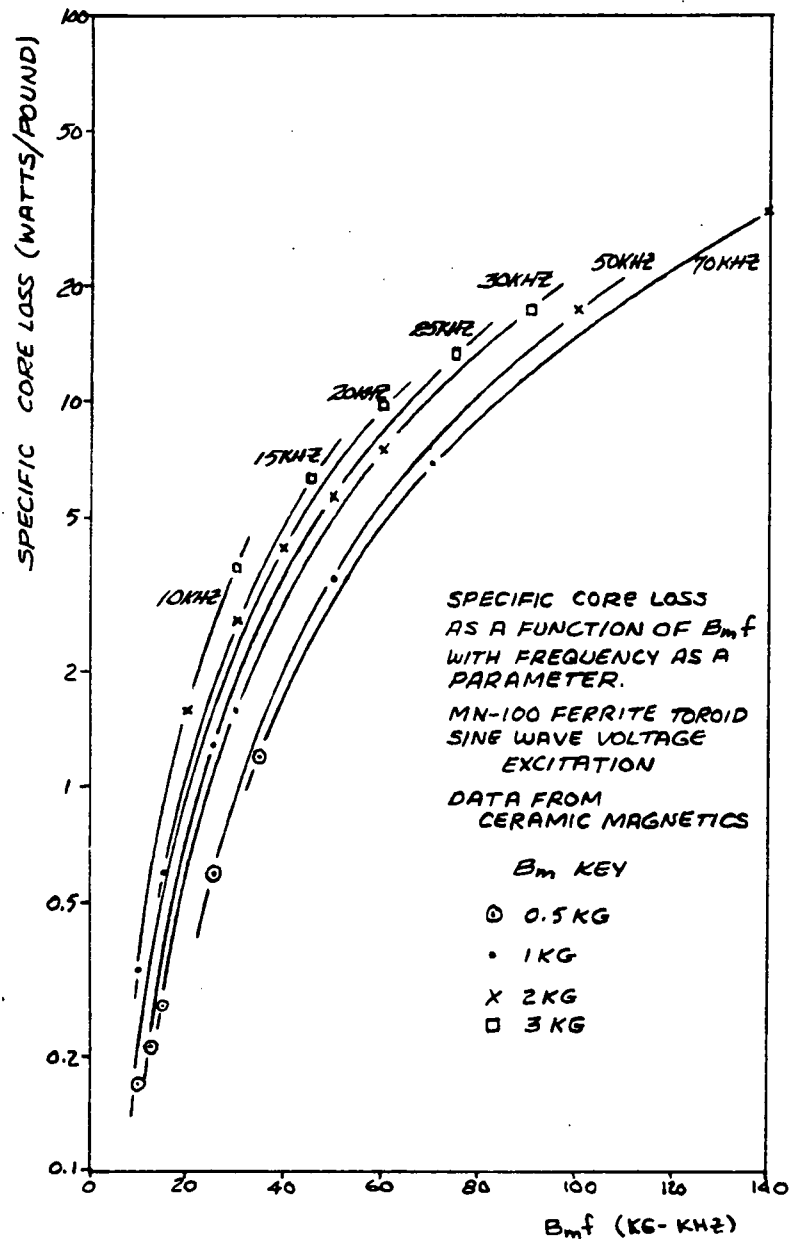


FIGURE 9
SPECIFIC CORE LOSS VS. $B_m f$, FREQUENCY A PARAMETER

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SPECIFIC CORE LOSS VS. $B_m f$, FREQUENCY A PARAMETER

FIGURE 10

B_m , and f , it is seen that the induced voltage E is a linear function of the $(B_m f)$ product. The data for the above four figures were taken from the manufacturer's literature, which in this case was Magnetics, Inc., Catalog MCC-100.

Figures 8, 9, and 10 are plots of specific core loss for a toroid core of MN-100 ferrite material run under sine wave voltage excitation and room temperature conditions. Figure 8 is a plot of specific core loss vs maximum flux density with frequency as the parameter. Both Figures 9 and 10 are a plot of specific core loss vs the $(B_m f)$ product with Figure 9 using linear scale paper and Figure 10 using semi-logarithmic paper. Again, as for the Permalloy 80 material, it is seen that the specific core loss of the MN-100 material is not a linear function of the $(B_m f)$ product. The data for Figures 8, 9, and 10 were obtained from literature supplied by the manufacturer, Ceramic Magnetics.

A direct comparison of the specific core loss characteristics for these two materials by the use of Figures 4 through 10 would, indeed, be desirable, but, unfortunately, such a comparison is not valid since the core geometries of the two materials are different. Nevertheless, certain conclusions can be made which are common to the specific core loss characteristics of both materials. As noted earlier, an increase in the $(B_m f)$ product can be accomplished in four different ways. The effect on the specific core loss for increasing $(B_m f)$ values will now be investigated. In addition, the effect on the specific core loss for an increase or decrease in either B_m or f such that the $(B_m f)$ product remains a constant will also be investigated.

Case 1: B_m Increases And f Remains Constant Such That $(B_m f)$ Increases

The curves in Figure 4 (Permalloy 80) and Figure 8 (MN-100) describe the above set of conditions, that is, each curve in both of these figures represents a constant frequency and motion from left to right on the graph, gives an increase in B_m with a subsequent increase in the $(B_m f)$ product. An analysis of both figures shows that the specific core loss always increases for the above set of conditions. For the curves in Figure 4 an increase by a factor of 2 in the $(B_m f)$ product causes the specific core loss to increase by a factor anywhere from 3.4 to 3.7. For the curves in Figure 8 an increase by a factor of 2 in the $(B_m f)$ product causes the specific core loss to increase by a factor between 4.2 and 5.9.

Case II: f Increases And B_m Remains Constant Such That $(B_m f)$ Increases

The curves in Figure 5 (Permalloy 80) describe the above conditions. Each curve in Figure 5 represents a constant maximum flux density, an increase in f from left to right, and a subsequent increase in the $(B_m f)$ product. A plot similar to Figure 5 for the MN-100 ferrite material was not made since it was anticipated that the MN-100 curves would be similar in nature to the Permalloy 80 curves. An analysis of the curves in Figure 5 shows that an increase in the $(B_m f)$ product by a factor of 2 causes the specific core loss to increase by a factor anywhere from 2.7 to 3.1. Using the data from Figure 8, an analysis of the MN-100 material shows that an increase in the $(B_m f)$ product by a factor of 2 causes the specific core loss to increase by a factor of 2.1 to 3.1.

A comparison of the results for the above two cases shows that the maximum flux density has a greater effect than does the frequency on the specific core loss for each of these two materials. This greater dependence on B_m than on f for the specific core loss will be even more evident in the following case.

Case III: B_m And f Either Increase Or Decrease Such That $(B_m f)$ Remains Constant

The curves in Figures 6 and 7 (Permalloy 80) and Figures 9 and 10 (MN-100) describes the above condition. In these four figures lines parallel to the specific core loss-axis are lines of constant $(B_m f)$. Upward motion on these lines gives decreasing f , increasing B_m and increasing SCL while downward motion gives increasing f , decreasing B_m , and decreasing SCL. Inspection of any one of these four figures readily shows that the lowest specific core loss for a given $(B_m f)$ value is obtained by using the highest frequency and the lowest maximum flux density. For example, from Figure 6 (Permalloy 80) for a $(B_m f)$ product of 50 it is found that for a change in frequency from 10 to 15 KHz, the specific core loss (SCL) decreases 17%; from 15 to 20 KHz, SCL decreases 9.2%; from 20 to 25 KHz, SCL decreases 11%; and from 25 to 50 KHz, SCL decreases 14%. The overall decrease in SCL from 10 to 50 KHz for this $(B_m f)$ product is 42%. Likewise, from Figure 8 (MN-100) for a $B_m f$ product of 50 it is found that for a change in frequency from 20 to 25 KHz, SCL decreases 15%; and from 25 to 50 KHz, SCL decreases 39%. The decrease in SCL from 20 to 50 KHz for MN-100 for a $B_m f$ product of 50 is 48%.

CASE IV: B_m and f both increase such that $(B_m f)$ increases

This case extends either Case I or Case II by removing the restriction that either f or B_m remains constant while the other increases. It follows then from the conclusions reached in Case I and II that the SCL will always increase with an increase in $(B_m f)$ when both B_m and f increase. An inspection of the curves in Figures 6,7,9 and 10 readily leads to the same conclusion.

CASE IV f Increases And B_m Decreases Such That $B_m f$ Increases

In cases I, II and IV, the relation between $(B_m f)$ and SCL was such that an increase in $(B_m f)$ caused an increase in SCL. In this case this relation does not always hold true; for it is also found that SCL can either remain constant or even decrease when $(B_m f)$ increases.

An inspection of Figures 6 and 7 (Permalloy 80) and Figures 9 and 10 (MN-100) shows that SCL can remain constant as f increases and B_m decreases such that $(B_m f)$ increases. That is, any line parallel to the $(B_m f)$ axis is a line of constant specific core loss and motion in the direction of increasing $(B_m f)$ gives increasing f and decreasing B_m . Specific illustrations which show the SCL can increase, remain constant, or decrease for the conditions of this case are given in Tables 4 through 9.

Both Table 4(Permalloy 80) and Table 5 (MN-100) show the same relation between $B_m f$ and SCL as was found in Cases I, II, and IV; that is, as $(B_m f)$ increases so also does SCL.

Table 4: Illustration Of An Increase In SCL When f Increases And B_m Decreases Such That $(B_m f)$ Increases For Permalloy 80 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
5	5	25	5.0
10	3.5	35	8.2
15	3.0	45	10.7
20	2.75	55	14.0
25	2.6	65	17.0
50	1.5	75	18.5

Table 5: Illustration Of An Increase In SCL When f Increases And B_m Decreases Such That $(B_m f)$ Increases For MN-100 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
10	3.0	30	3.7
15	2.67	40	4.9
20	2.5	50	6.7
25	2.4	60	8.4
30	2.33	70	10.5
50	1.6	80	10.8

The data in Table 6 (Permalloy 80) for a constant SCL of 10 watts/lb. shows that $B_m f$ increases 36% for a 73% decrease in B_m and a factor of 5 increase in f . The data in Table 7 (MN-100) for a constant SCL of 3 watts/lb. shows that $(B_m f)$ increases 72% for a 66% decrease in B_m and a factor of 5 increase in f .

Table 6: Illustration Of Constant SCL When f Increases And B_m Decreases Such That $(B_m f)$ Increases For Permalloy 80 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
10	3.9	39.	10
15	2.87	43.	10
20	2.28	45.5	10
25	1.94	48.5	10
50	1.06	53.	10

Table 7: Illustration Of Constant SCL when f Increases And B_m Decreases Such That $(B_m f)$ Increases For MN-100 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
10	2.70	27.	3
15	2.10	31.5	3
20	1.73	34.5	3
25	1.46	36.5	3
30	1.33	40.	3
50	0.93	46.5	3

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The data in Table 8 (Permalloy 80) shows that SCL decreases 25% while $(B_m f)$ increases 15% for a 77% decrease in B_m and a factor of 5 increase in f . The data in Table 9 (MN-100) shows that SCL decreases 43% while $(B_m f)$ increases 33% for a 73% decrease in B_m and a factor of 5 increase in f . Both Tables 8 and 9 show that the rate of increase in $(B_m f)$ must be relatively small in order for SCL to show a decrease.

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Table 8 : Illustration Of A Decrease In SCL When f Increases
And B_m Decreases Such That $(B_m f)$ Increases For
Permalloy 80 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
10	5.2	52	16.7
15	3.6	54	15.1
20	2.8	56	14.5
25	2.3	58	13.9
50	1.2	60	12.5

Table 9: Illustration Of A Decrease In SCL When f Increases
And B_m Decreases Such That $(B_m f)$ Increases For
MN-100 Material

f (KHz)	B_m (KG)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
10	3.0	30	3.7
15	2.13	32	3.1
20	1.7	34	3.0
25	1.44	36	2.9
30	1.27	38	2.3
50	0.80	40	2.1

Case VI B_m Increases and f Decreases Such That $(B_m f)$ Increases

An analysis of Figures 6 and 7 (Permalloy 80) and Figures 9 and 10 (MN-100) shows that SCL increases when B_m increases and f decreases such that $(B_m f)$ increases. Thus, the relation here of an increase in $(B_m f)$ giving rise to an increase in SCL is the same as was found in Case I, II and IV. In a previously made comparison between Case I and Case II it was found that B_m has a greater effect than does the frequency on the specific core loss. Here again, the results of this case and Case V clearly shows that B_m has a greater effect than does f on SCL.

The results of the seven cases discussed above are summarized in Table 10.

Table 10: Summary Of Results For Cases I Through VI

CASE NO.	B_m (KG)	f (KHz)	$B_m f$ (KG-KHz)	SCL (Watts/Lb.)
II	Constant	Increases	Increases	Increases
I	Increases	Constant	Increases	Increases
IV	Increases	Increases	Increases	Increases
VI	Increases	Decreases	Increases	Increases
III	Increases	Decreases	Constant	Increases
III	Decreases	Increases	Constant	Decreases
V	Decreases	Increases	Increases	Increases, remains constant or decreases

4.2.2 Skin Effect

Skin effect is a phenomenon which tends to concentrate the current in a thin layer or skin near the conductor's surface as the frequency of the alternating current increases. The currents concentrate on the conductor's surface nearest to the field source producing the currents. The field source is the varying magnetic field produced within the conductor by its own current.

Because of skin effect, the current density is not uniform over the cross-sectional area of the conductor. Consequently, the effective resistance of the conductor may be appreciably greater for alternating current than for direct current so that the heat loss per ampere may be appreciably greater for alternating current.

The distance the current penetrates the surface of the conductor is known as depth of penetration or skin depth. For a plane solid conductor of infinite depth and with no field variation along the width or length dimension it can be shown (See for example, *Fields and Waves In Modern Radio*, by Ramo and Whinnery, 2nd Edition, 1958, pages 230 - 253, John Wiley & Sons) that for a field of sinusoidal variation the depth of penetration is given by

$$d = (\pi f \mu \sigma)^{-1/2} \quad (4.4)$$

where

- d = Depth penetration or skin depth (meters)
- f = Frequency (hertz)
- μ = Permeability (henrys/meter)
- σ = Conductivity (ohm⁻¹ meter⁻¹)

Inspection of Equation 4.4 shows that the depth of penetration is smaller the higher the conductivity, the higher the permeability, and the higher the frequency since d is inversely proportional to the square root of each of these.

In the derivation which leads to Equation 4.4, it is shown that the magnitude of the current decreases exponentially with penetration into the conductor. The skin depth d is defined as the depth or the distance at which the current density has decreased to $1/e$ of its value at the surface.

As noted above, Equation 4.4 applies strictly to plane solids. This equation may, however, be extended to conductors of other shapes so long as the calculated value of d is much smaller than any curvature of the surfaces. For a circle the curvature is constant and is given by the reciprocal of the radius. Thus the smaller the radius of the wire, the better is the approximation.

Solving Equation 4.4 for the frequency we have

$$f = \frac{1}{\pi \mu \delta d^2} = \frac{\rho}{\pi \mu d^2} \quad (4.5)$$

where $\rho = 1/\delta = \text{Resistivity (ohm meter)}$

If the skin depth is expressed in inches then Equation 4.5 becomes

$$f = \frac{1550 \rho}{\pi \mu d^2} \quad (4.6)$$

The resistivity of copper at 20°C is 1.7241×10^{-8} ohm meter and if $\mu = \mu_o = 4\pi \times 10^{-7}$ henrys/meter, then Equation 4.6 becomes

$$f = \frac{6.7692}{d^2} \quad (4.7)$$

The maximum value of the frequency which would give no skin effect would occur when the skin depth is equal to the radius of the wire.

Then by Equation 4.7 the maximum frequency for no skin effect is

$$f_{\max} = \frac{6.7692}{d_{\max}^2} \quad (4.8)$$

where $d_{\max}$ is the maximum depth of penetration and is equal to the radius of the conductor. By means of Equation 4.8 the maximum frequency for no skin effect for round copper wire sizes of 10 - 22 AWG is given in Table 11. The same information is given in Figure 11 where the frequency is plotted against the AWG wire size.

TABLE 11
Maximum Frequency For No Skin Effect For Round Copper Wire
Sizes 10 -22 AWG

Wire Size (AWG)	Nominal Wire Diameter (Inches)	$d_{max} = r$ (Inches)	f_{max} (KHz)
10	0.1019	0.0509	2.61
12	0.0808	0.0404	4.15
14	0.0641	0.0320	6.61
15	0.0571	0.0285	8.33
16	0.0508	0.0254	10.5
17	0.0453	0.0226	13.2
18	0.0403	0.0201	16.8
19	0.0359	0.0180	20.9
20	0.0320	0.0160	26.4
21	0.0285	0.0142	33.6
22	0.0253	0.0126	42.6

The graph in Figure 11 shows that if a given wire size is used at a frequency which lies on or below the curve, then the skin effect can be neglected. In this case the DC resistance can be used to compute the I^2R loss. However, if the given wire size is used at a frequency which lies above the graph then the skin effect can be appreciable. In this case, the AC resistance must be used to compute the I^2R loss.

To determine how appreciable the skin effect is on the conductor loss, the ratio of AC resistance to DC resistance is computed. This ratio is computed as follows:

$$R_{DC} = \frac{\rho l}{b_{DC}} \quad (4.9)$$

$$R_{AC} = \frac{\rho l}{b_{AC}} \quad (4.10)$$

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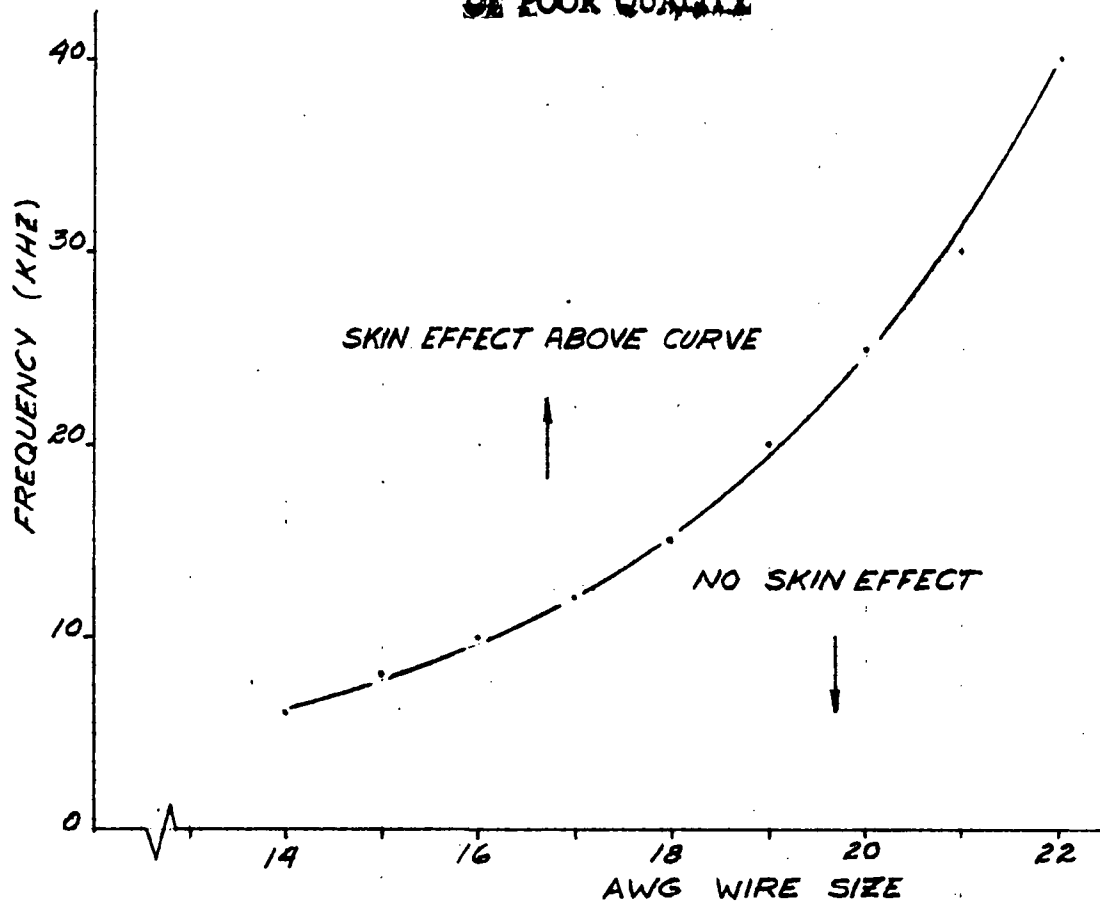


FIGURE 11
ZERO SKIN EFFECT FREQUENCIES
FOR VARIOUS COPPER WIRE SIZES

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where

- ρ = Resistivity (ohm meter)
 l = Length of conductor (meters)
 b_{DC} = Cross-sectional area of conductor (meter²)
 b_{AC} = Effective cross-sectional area of conductor (meter²).

For a circular wire of radius r , then

$$b_{DC} = \pi r^2 \quad (4.11)$$

$$b_{AC} = \pi r^2 - \pi (r - d)^2 = \pi (2r - d) d \quad (4.12)$$

where d is the depth of penetration. Substituting Equation 4.11 in Equation 4.9 and Equation 4.12 into Equation 4.10 and then taking the ratio of Equation 4.10 to Equation 4.9 gives

$$\frac{R_{AC}}{R_{DC}} = \frac{\frac{\rho l}{\pi (2r - d) d}}{\frac{\rho l}{\pi r^2}} = \frac{r^2}{(2r - d) d} \quad (4.13)$$

Solving Equation 4.7 for the skin depth, we have

$$d = \frac{2.6018}{f^{1/2}} (1 \text{ m}) \quad (4.14)$$

By means of Equation 4.13 and Equation 4.14, Table 12 is constructed. Table 12 gives the ratio of AC resistance to DC resistance of round copper conductors for wire sizes 10 - 22 AWG.

TABLE 12

Ratio Of AC Resistance To DC Resistance Of Round Copper Conductors
For Wire Sizes 10 - 22 AWG And Frequencies 5 - 40 KHz

Wire Size (AWG)	Frequency KHz				
	5	10	20	30	40
10	1.08	1.31	1.69	1.99	2.24
12	1.01	1.15	1.42	1.65	1.85
14	1.00	1.04	1.22	1.40	1.54
15	1.00	1.01	1.14	1.30	1.42
16	1.00	1.00	1.08	1.20	1.31
17	1.00	1.00	1.04	1.12	1.22
18	1.00	1.00	1.01	1.07	1.14
19	1.00	1.00	1.00	1.03	1.08
20	1.00	1.00	1.00	1.00	1.04
21	1.00	1.00	1.00	1.00	1.01
22	1.00	1.00	1.00	1.00	1.00

Table 12 readily shows that the AC resistance, and consequently the conductor loss, becomes quite appreciable for the larger diameter wires at the higher frequencies. It is also seen from Table 12 that the skin effect becomes less appreciable for the smaller diameter wires even at the higher frequencies. Thus, if large conductors are required to be used at high frequencies the winding should be multifilar (two or more parallel wires) or should consist of Litz wire, which is made up of multiple strands of insulated fine wires.

4.3 Comparison of Core Temperature Rise for Different Core Materials

In a transformer exposed to the vacuum of space, cooling by convection is non-existent and within the normal restrictions of temperature extremes, cooling by radiation directly from core and coil is minor. Conduction of heat through the core to a heat sink, therefore, becomes the major mechanism of cooling. It is of practical importance, therefore, to

- 1) calculate the temperature rise of the core due to core loss,
- 2) compare the temperature rise of core materials having different thermal conductivities.

For the following discussion a C-core geometry is used and the following assumptions are made:

- 1) The gap is in the center of the core,
- 2) The hottest spot occurs in the vicinity of the gap,
- 3) The heat representing one-fourth of the total core loss flows from the gap area along the core to the center of the exposed section of the core,
- 4) The path for heat flow equals one-fourth the mean length of the core.

The following symbols are used in the discussion:

$$\begin{aligned}
 D &= \text{Density of core (lb./in.}^3\text{)} \\
 A_c &= \text{Cross-sectional area of core (in.}^2\text{)} \\
 (SCL)_w &= \text{Specific core loss (watts/lb.)} \\
 (SCL)_v &= \text{Specific core loss (milliwatts/cm}^3\text{)} \\
 \ell &= \text{Mean magnetic length of core (in.)} \\
 \alpha &= \text{Length for heat conduction} = \frac{1}{4}\ell \text{ (in.)} \\
 K &= \text{Thermal conductivity of core} \left(\frac{\text{watt-in.}}{\text{in.}^2 \text{ } ^\circ\text{C}} \right)
 \end{aligned}$$

$$\Delta T = \text{Temperature rise of core (} ^\circ\text{C} \text{)}.$$

The specific core loss of core materials is generally expressed in watts/lb. in the vendor's literature. An exception is for ferrite materials and for these the specific core loss is generally expressed in milliwatts/cm³.

If the specific core loss is expressed in watts/lb. then,

$$\text{Weight of } \frac{1}{4} \text{ core} = D A_c \alpha$$

$$\text{Watts loss of } \frac{1}{4} \text{ core} = D A_c (SCL)_w \alpha$$

so that

$$\Delta T = \frac{D A_c \alpha (SCL)_w \alpha}{2 K A_c} = \frac{D \alpha^2 (SCL)_w}{2 K} \quad (4.15)$$

If the specific core loss is expressed in mw/cm^3 , then

$$\text{Volume of } 1/4 \text{ core} = A_c \chi$$

$$\text{Watts loss of } 1/4 \text{ core} = (2.54)^3 A_c \chi (\text{SCL})_v \times 10^{-3}$$

so that

$$\Delta T = \frac{(2.54)^3 A_c \chi (\text{SCL})_v \chi}{2K A_c} = \frac{16.387 \chi^2 (\text{SCL})_v \times 10^{-3}}{2K} \quad (4.16)$$

The relationship between $(\text{SCL})_v$ and $(\text{SCL})_w$ can be determined by the use of Equations 4.15 and 4.16 and it is found to be,

$$(\text{SCL})_v = \frac{D(\text{SCL})_w \times 10^3}{16.387} \quad (4.17)$$

It is interesting to note from Equation 4.15 and Equation 4.16 that the temperature rise of the core can be expressed in terms of the dimension of length (thermal flow length) without direct reference to cross-sectional area of the core.

The ΔT so calculated by either Equation 4.15 or Equation 4.16 is useful in selecting a core consistent with allowable temperature rise as well as in the evaluation of various core materials. In actual practice it will vary somewhat depending on the precise means for the conduction of heat to the heat sink.

A comparison of the ΔT 's of Permalloy 80 and MN-100 will now be made. This comparison can best be made by finding the ratio of ΔT of Permalloy to ΔT of MN-100.

The vendor's literature on Permalloy 80 expresses the specific core loss in watts/lb. This material's density is 0.316 lbs./in.^3 and its thermal conductivity is $0.702 \text{ (watt in./in.}^2 \text{ }^\circ\text{C)}$. Thus, by Equation 4.15,

$$(\Delta T)_P = 0.225 \chi_P^2 (\text{SCL})_{wP} \quad (4.18)$$

where the subscript P is for Permalloy 80.

The vendor's literature on MN-100 ferrite expresses the specific core loss in milliwatts/cm³. The thermal conductivity of MN-100 is 0.159 (watt in/in.² °C). Thus, for MN-100, Equation 4.16 becomes,

$$(\Delta T)_F = 0.0515 \chi_F^2 (SCL)_{wF} \quad (4.19)$$

where the subscript F is for MN-100 ferrite.

The density of MN-100 is 0.166 lbs./in.³. Thus the density of Permalloy 80 is 1.7 times the density of MN-100. It should also be noted that the thermal conductivity of Permalloy is 4.4 times the thermal conductivity of MN-100.

The substitution of the density of MN-100 into Equation 4.17 and subsequently substituting Equation 4.17 into Equation 4.19 gives,

$$(\Delta T)_F = 0.5222 \chi_F^2 (SCL)_{wF} \quad (4.20)$$

The specific core loss in Equation 4.18 and Equation 4.20 are now in the same units. Taking the ratio of Equation 4.18 to Equation 4.20 gives,

$$\frac{(\Delta T)_P}{(\Delta T)_F} = 0.43 \frac{\chi_P^2 (SCL)_{wP}}{\chi_F^2 (SCL)_{wF}} \quad (4.21)$$

Now suppose the Permalloy 80 and the MN-100 cores each have the same thermal path length, that is $\chi_P = \chi_F$. If the (ΔT) for each of these cores is to be the same, then by Equation 4.21 it is seen that

$$(SCL)_{wF} = 0.43 (SCL)_{wP} \quad (4.22)$$

Thus, if the thermal path length of each core is the same, then the specific core loss of MN-100 must be 57% less than that for Permalloy 80 in order to give the same ΔT .

To overcome the low thermal conductivity of ferrite MN-100, copper laminates may be bonded to two opposite surfaces of the ferrite to make the combination equal to Permalloy 80 in thermal conductance.

The required thickness of copper is calculated by using Equation (3-16) with appropriate subscripts. Thus

$$K_P = \frac{K_F t_F + K_C t_C}{t_F + t_C} \quad (4.23)$$

where the subscripts P, F, and C refer to Permalloy 80, MN-100 ferrite, and copper respectively. The combined ferrite and copper thickness is equal to the Permalloy thickness. Thus,

$$t_F = t_P - t_C \quad (4.24)$$

Substituting equation (4.24) into equation (4.23) and solving for t_C gives.

$$t_C = \left(\frac{K_P - K_F}{K_C - K_F} \right) t_P \quad (4.25)$$

For the following thermal conductivities expressed in units of $\frac{\text{watts} \times \text{in.}}{\text{in}^2 \times \text{deg. C}}$: $K_P = 0.702$, $K_F = 0.159$ and $K_C = 9.7$, and for $t_P = 1$ inch,

then by equations (4.25) and (4.24) we have

$$t_C = \left(\frac{0.702 - 0.159}{9.7 - 0.159} \right) = 0.0569 \text{ (in.)}$$

$$t_F = 1 - 0.059 = 0.943 \text{ (in.)}$$

Thus, two copper laminations, each 0.0285 inches thick, laminated to 0.943 inches of MN-100 ferrite will be equal in thermal conductance to Permalloy 80 of 1-inch thick.

An additional factor influencing the temperature rise of ferrite cores is the increased core loss exhibited by these materials at elevated temperature. In contrast, the losses of Permalloy are affected only to a minor degree by temperature. Additional information covering the losses of ferrites over a range of temperature, frequency, flux density and wave form are needed to fill in the gaps in existing knowledge.

5.0 EXPERIMENTAL PROGRAM

5.1 Purpose

The experimental program was set up for the purpose of accomplishing three objectives:

- a) To establish reliable design criteria for maximum voltage stresses capable of yielding corona-free operation of the transformer at atmospheric pressure
- b) To design a process of impregnation/encapsulation that would yield maximum corona inception and extinction voltages.
- c) To select suitable insulating materials for both open and encapsulated construction.

5.2 Evaluation Of Materials

Materials evaluated under the program included the following:

5.2.1 Layer Insulation

- a) Micanite 11X-4724, a mica splittings product
- b) Isomica 4350, a laminate of reconstituted mica paper and woven fiberglass, silicone impregnated
- c) Polyimide Film, Kapton H
- d) Nomex 410, polyamide paper
- e) Interleaved Kapton-H and non-woven polyester web (Pellon 7200)
- f) Midwest 22-05-014545, a silicone treated fiberglass-mica paper composite.

5.2.2 Impregnating/Encapsulating Compounds

- a) Epoxies - Scotchcast 235 and 251
- b) Polyurethanes
 - Conap 2524, 2522, 2526
 - Baker 20
- c) Silicones
 - Dow Corning R-7521
 - Dow Corning Sylgard 184.

5.3 Tests On Unimpregnated Coils

5.3.1 Calibration Of The Corona Detector

A number of corona test coils were wound following the procedure of Section 5.3.2 and measured for capacitance between windings. The capacitance varied from 28 pF to 92 pF, depending on the thickness of the insulation.

The calibration of the corona test equipment was accomplished following the procedure of ASTM D1868-73, Figure 1, and described in Appendix D of the present report.

The specimen coils were connected in series with the square wave output of the Model 532 Tektronix Oscilloscope to the high voltage terminals of the corona detector. Square wave voltages of .1, .2, .5, and in some cases 1.0 volts were applied to the specimen coils and the deflection of the pulses on the CRT of the corona detector were measured. Sensitivity in volts/inch was calculated and by multiplying by the capacitance of the test coil in picofarads, the sensitivity in picocoulombs/inch was derived. The results are presented in Table 13.

In interpreting the results of Table 13, it should be noted that the accuracy of measurement of deflections in the order of $4/32$ inch and less is very poor. Furthermore, it was observed that the linearity of deflections greater than about $10/32$ inch was impaired, due probably to loading of the amplifier. Therefore, in calculating the results in terms of picocoulombs/inch, only deflections between 5.5 and 12 thirtyseconds of an inch were used. It was found that within the limits of error, the sensitivity of the equipment was essentially constant at between 70 and 84 picocoulombs per inch in the range of capacitance 28 to 92 picofarads, or approximately 10 picocoulombs for a deflection of $1/8$ inch.

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TABLE 13
RESULTS OF CORONA DETECTOR CALIBRATION

Specimen Number	Capacitance (pF)	Test Voltage (Volts)	Oscilloscope Deflection (in./32)	Volts/Inch	Charge (Picocoulombs)	Picocoulombs/in.
K006	92	.1	4	.80	9.2	83.6
		.2	7	.91	18.4	
		.5	15	1.07	46.0	
K008	58	.1	2.5	1.28	5.8	84.0
		.2	5	1.28	11.6	
		.5	11	1.45	29.0	
K010	48	.1	2	1.60	4.8	76.7
		.2	4	1.60	9.6	
		.5	10	1.60	24.0	
K012	66	.1	3	1.07	6.6	76.8
		.2	5.5	1.16	13.2	
		.5	12.	1.33	33.0	
K026	41	.1	1.5	2.14	4.1	82.0
		.2	3	2.14	8.2	
		.5	8	2.00	20.5	
K032	31	.1	1	3.20	3.1	70.5 83.0
		.2	2.5	2.56	6.2	
		.5	7	2.28	15.5	
		1.0	12	2.66	31.	
K040	28	.1	1	3.20	2.8	74.3 81.2
		.2	2.5	2.56	5.6	
		.5	6	2.66	14.0	
		1.0	11	2.90	28.0	

5.3.2 Corona Tests For Various Creepage Distances

Creep distance tests were conducted on coils wound on coil forms using two wire sizes: Number 18 and Number 30 AWG heavy film coated. Corona inception voltages were determined between adjacent windings spaced 1/8, 1/4, 3/8, and 1/2 inches apart. The results are presented in Table 14, and are plotted graphically in Figure 3 Section 4.1.

TABLE 14
EFFECT OF CREEP DISTANCE ON CORONA INCEPTION VOLTAGE

Specimen Number	Wire Size	Creep Distance (Inches)	Corona Inception Voltage (Volts)	Average CIV Stress * (Volts/Mil)
1a	18	1/8	4750	38
1b	18	1/4	6200	25
1c	18	3/8	7500	20
1d	18	1/2	9000	18
1e	30	1/8	3100	25
1f	30	1/4	4100	16
1g	30	3/8	7500	20
1h	30	1/2	8500	17

$$* \text{Average CIV Stress} = \frac{\text{CIV}}{\text{distance}}$$

5.3.3 Corona Tests On Layer Insulation

In order to obtain design criteria for layer insulation voltage stresses in open transformers, corona tests were performed on coils consisting of two concentric layers of Number 25 HML wire with various types and thicknesses of insulation between layers. Margins of at least 1/2 inch were maintained on the top layer to prevent corona along the creepage path to the edge of the coil. Corona inception voltages (CIV) and corona extinction voltages (CEV) observed on five types of insulation tested under the contract are presented in Table 15 (A-E). Corona inception voltages are plotted against thickness of insulation for four materials in Figure 12. Additional results obtained on Nomex 410 aramid-paper are plotted in Figure 2, Section 4. The corona inception voltages of Nomex and Kapton are seen to be comparable, and are higher than those of the other materials tested.

TABLE 15
RESULTS OF CORONA TESTS ON UNIMPREGNATED LAYER INSULATION
15A - KAPTON H-FILM, 2 MILS (DuPONT)

Number Of Layers	Total Thickness (Inches)	CIV (Volts)	CEV (Volts)	Average CIV Stress (Volts/Mil)
3	.006	1280	1180	214
4	.008	1375	1350	172
5	.010	1440	1370	144
6	.012	1470	1370	123
7	.014	1580	1550	113
10	.020	1925	1825	96
13	.026	2300	2200	89
16	.032	2550	2400	80

TABLE 15 (Continued)

15B - MICANITE 1I - X 4724, 6.5 MILS (3M COMPANY)

Number Of Layers	Total Thickness (Inches)	CIV (Volts)	CEV (Volts)	Average CIV Stress (Volts/Mil)
1	.0065	1025	975	158
2	.0130	1125	1075	87
3	.0195	1375	1300	70
4	.0260	1525	1425	59
5	.0325	1900	1800	59

15.C - ISOMICA 4350, 5.3 MILS (3M COMPANY)

2	.0106	1050	1025	99
4	.0212	1475	1450	70
6	.0318	2250	2175	71
8	.0424	2600	2400	61

15D - SILICONE TREATED FIBERGLASS-MIC A PAPER COMPOSITE, 10 MILS, MIDWEST MICA AND INSULATION CO., PRODUCT 22-05-014545

1	.010	1280	1210	128
2	.020	1500	1450	75
3	.030	1800	1750	60
4	.040	2400	2250	60

TABLE 15(Continued)

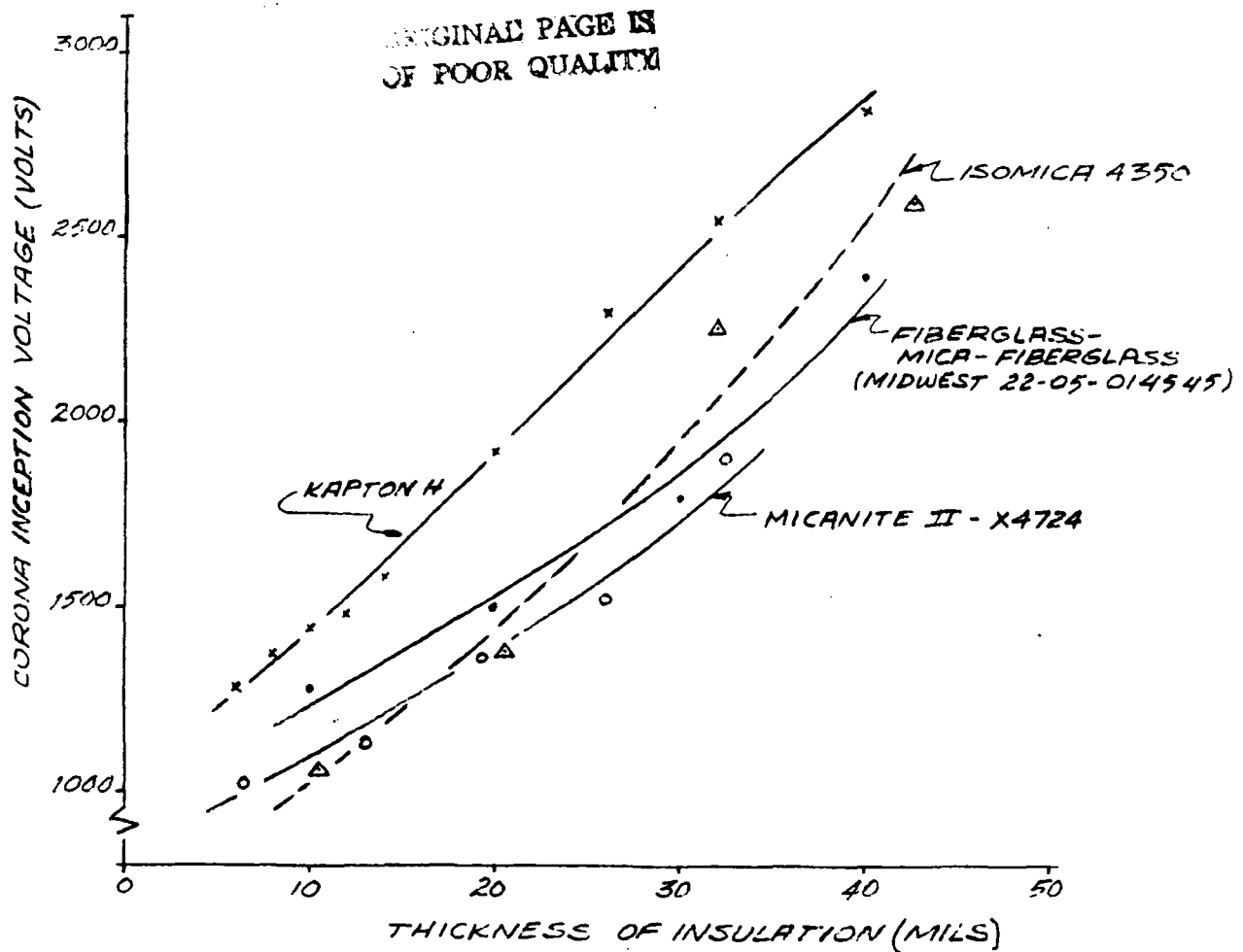
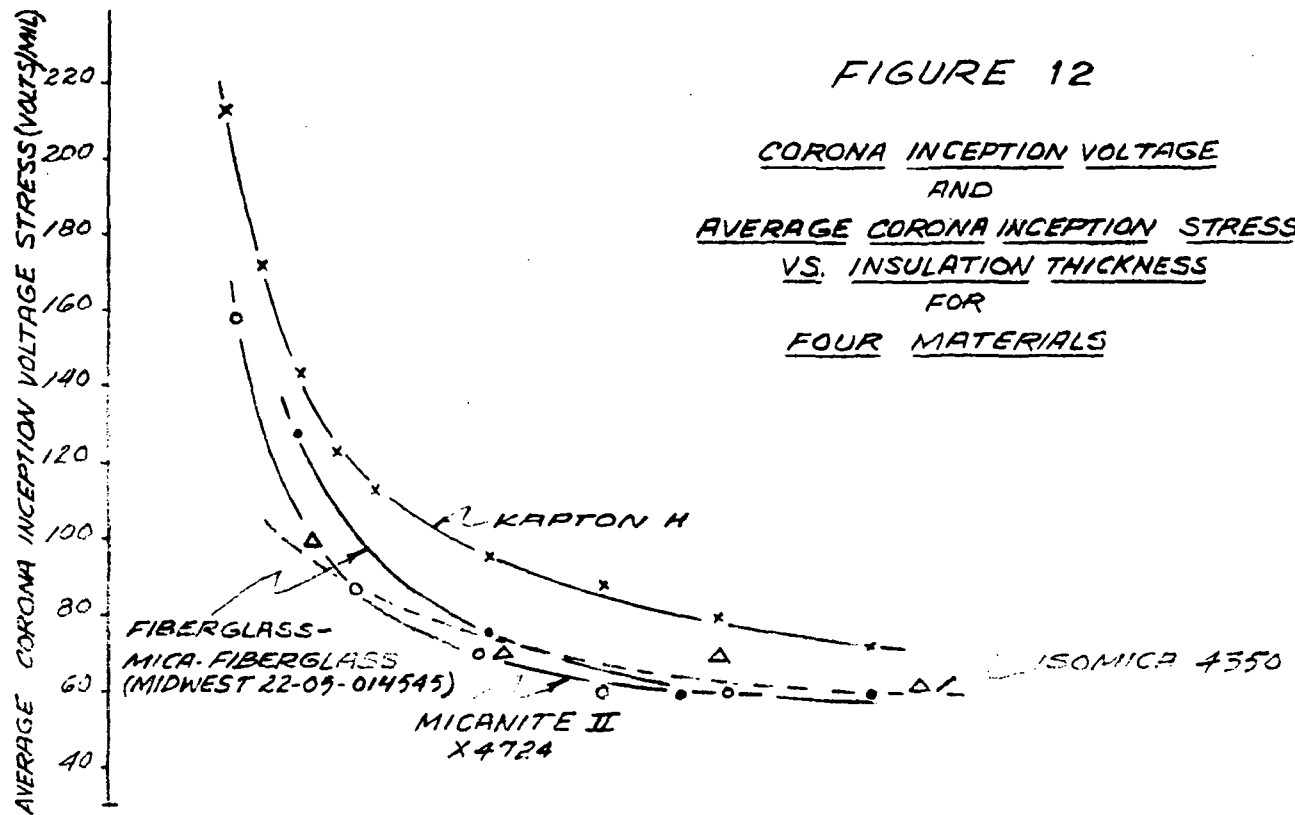
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15E - NOMEX 410, 2 AND 3 MILS (DuPONT)

Number Layers X Thickness	Total Thickness (inches)				
		Undried Coils		Dried Coils	
		CIV/CEV (Volts)	Average CIV/ CEV Stress (Volts/Mil)	CIV/CEV (Volts)	Average CIV/ CEV Stress (Volts/Mil)
2 x .003	.006	1190/1160	198/193	1290/1150	215/192
5 x .002	.010	1560/1500	156/150	1750/1710	175/171
4 x .003	.012	1625/1575	135/131		
10 x .002	.020	2000/1900	100/95	2400/2300	120/115
8 x .003	.024	2250/2200	94/92		
10 x .003	.030	2700/2500	90/83	3000/2950	100/98
16 x .002	.032	2900/2700	90/84	3100/2500	97/78
12 x .003	.036	2600/2550	72/71		
19 x .002	.038	2800/2700	74/71	3700/2200	97/58
16 x .003	.048	3000/2800	62/58		

FIGURE 12

CORONA INCEPTION VOLTAGE
AND
AVERAGE CORONA INCEPTION STRESS
VS. INSULATION THICKNESS
FOR
FOUR MATERIALS



5.3.4 Correlation Of Experimental Results With Calculated Voltage Gradients

Corona inception voltages determined experimentally for Kapton and Nomex showed some scatter but were essentially equal and are plotted on a common curve in Figure 2. The corona starting voltages were taken from Figure 2 and are tabulated in Table 16, in which is presented also the formula for calculating voltage gradient taken from Reference 13 and the calculated gradients on the surface of the wire. Total thickness of insulation includes the interlayer insulation and the 2 mils of wire coating.

An inspection of the results shows the corona inception voltage gradient to be between 157.0 and 167.7 volts per mil with a mean of 162.4 and a deviation of $\pm 3.3\%$. The significance of this result is that an unimpregnated coil wound with Number 25 HML wire with interlayer insulation consisting of Kapton or Nomex will be corona free provided that the maximum calculated gradient on the surface of the wire does not exceed 157 volts per mil. The same maximum gradient will apply to other geometries; for example, for end turns between successive layers having the same margin, the cylinder to cylinder configuration would apply, formulae for which are given in Reference 13 and other electrical engineering texts.

The precise value of the maximum corona-free gradient will vary with the nature of the dielectric and, for magnet wires, to a lesser extent with the thickness of the insulating coating on the wire. For bare wire with air dielectric the gradient is 75 volts per mil; for insulated wires a higher value may be expected. Porous insulations will have a lower corona-free gradient than solid film depending on the percentage of air in the total volume of insulation.

For a given insulation system the maximum corona-free gradient may be determined experimentally and this value used as a dependable design tool eliminating the guess-work that has accompanied the use of rule-of-thumb methods such as the average volts-per-mil concept.

TABLE 16

CALCULATED CORONA STARTING GRADIENTS FOR UNIMPREGNATED INSULATION

(Based on Experimental Data Plotted in Figure 2)

Wire: Number 25 HML Diameter Copper = .018 inches,
Insulation = .002 inches

Layer Insulation: Kapton H-Film, thickness 2 mils

$$E = \frac{.9V}{r \log_n \left(\frac{x}{r} + 1 \right)} \quad (\text{cylinder to plane})$$

E = voltage gradient (volts/mil)

V = applied voltage (volts)

r = radius of bare wire (mils)

x = distance, conductor to plane (mils)

Total Insulation Thickness, (mils)	Experimental Corona Inception Voltage, V (Volts)	Calculated Voltage Gradient on Conductor, E (volts/mil)
12	1400	165.5
22	2000	161.9
32	2540	167.7
42	2830	163.3
52	3000	157.0

Mean Calculated Voltage Gradient = 162.4 volts/mil $\pm$ 3.3%

5.4 Experimental Program On Encapsulated Coils

An experimental program was undertaken for the purpose of investigating materials and processes capable of yielding the highest corona inception voltages in coils typifying those of the contract transformers.

Experiments were conducted on specimen coils utilizing a number of different resins and two types of processes. The first was a two-stage process whereby the coils were first impregnated under vacuum in a low viscosity but relatively high weight loss unfilled compound, cured, and subsequently encapsulated in a low weight loss filled encapsulant. In the second process, impregnation and encapsulation were accomplished simultaneously in a low viscosity, low weight loss filled epoxy. Impregnants tested in the first process included an epoxy, Scotchcast 235, and several polyurethanes of the Conap EN-2500 series. The encapsulant used in both processes was Scotchcast 251, a 3M product.

5.4.1 Construction Of Specimen Coils

Early experiments using the insulations listed in Section 5.2.1, gave low corona inception voltages due to incomplete impregnation. Subsequent tests, which used only interleaved layers of Kapton H and Pellon 7200 non-woven polyester web, gave higher corona inception voltages.

Coils for the encapsulation tests were wound in accordance with the following procedure.

SPECIMEN COIL CONSTRUCTION PROCEDURE

MATERIALS

Polyimide-fiberglass (0.032 inch thick) coil forms, 1 inch x 1 inch cross section; 2 1/4 inches in length

HML wire, Number 25 AWG

Kapton H film, 2 mil, 5 mil, width 2 1/8 inches

Polyester web, Pellon 7200, width 2 1/8 inches

Nomex lacing tape, Gudebrod R & D 1141

Kapton pressure sensitive tape, acrylic adhesive, width 3/8 inch.

CONSTRUCTION

Alternate layers of Kapton film and Polyester web equal in number to those of the insulating layer to be tested are wrapped over the coil form and secured temporarily on the right-hand side with Kapton tape. A single layer of Number 25 HML wire is wound over the outside Kapton layer, winding from left to right. The start of the winding is secured with Nomex lacing tape by tying the tape over the first turn and winding succeeding turns over about 1 inch of tape. One-eighth inch margins are provided on both sides of the winding. The Kapton tape used to secure temporarily the insulation is removed prior to completing the winding, and the finish turn is secured by winding the final half-inch of the coil wire over a loop of the Nomex lacing tape, inserting the final turn through the loop, and pulling the loop tight to secure the end turn.

After completing the single layer winding, the desired number of layers of polyester web and Kapton film are wrapped over the winding and secured temporarily with the Kapton adhesive tape. A second layer of Number 25 HML wire is wound over the Kapton, with 1/4 inch margins and a winding width of 1 1/2 inch, securing start and finish leads with Nomex lacing tape as in the first layer.

SPECIMEN COIL CONSTRUCTION PROCEDURE (Continued)

All adhesive tapes used for temporarily securing parts must be removed before completion of the coil. An outside wrapper consisting of the same thickness of insulation as was used between windings is placed over the second winding and secured in place with several turns of Nomex lacing tape.

Start and finish leads are cut to a length of 3 inches, the ends are stripped of insulation, and both windings are shorted for the corona test by twisting the ends of the leads together.

5.4.2 Two-Stage Process Using Scotchcast 235 As The Impregnant

The first experiments were conducted using Scotchcast 235 as the impregnant. The coils were dried overnight at 110°C , placed under vacuum for 3 - 4 hours and the compound was introduced under vacuum. The coils were removed from the vacuum tank and allowed to soak for two hours while covered with the compound at 75°C . They were then drained and cured overnight at 75°C . Low corona inception voltages of coils treated in this manner were attributed to drainage of the compound during the several hours prior to gelation.

The alternative process of encapsulation without prior cure of the impregnating resin was rejected because of the likelihood of creating outgassing problems due to the low density impregnant rising to the surface of the encapsulant.

5.4.3 Two-Stage Process Using Polyurethane Impregnant

Subsequent tests were carried out using as impregnants room temperature curing polyurethanes Conap EN-2522, EN-2524 and a blend of equal parts of EN-2524 and EN-2526. The principal difference in these materials is with respect to pot life, which is approximately 30 minutes for EN-2524, 60 minutes for EN-2522, and 120 minutes for the blend. EN-2526 is a hard resin with a recommended cure temperature of 60°C but blended with EN-2524 the mixture cures to an elastomer at room temperature.

The specimen coils were impregnated under vacuum, cured and potted in accordance with Process Specification 102 which appears on the following pages.

PROCESS SPECIFICATION MC-102

TWO-STAGE PROCESS FOR THE IMPREGNATION AND ENCAPSULATION OF COILS FOR SPACE-TYPE MAGNETIC COMPONENTS

EQUIPMENT

Vacuum tank with pump capable of evacuation to 2 Torr or less, equipped with vacuum gauge and disposable plastic tube (polyethylene) for introduction of impregnating resin while maintaining the coils under vacuum.

Air circulating oven.

Scales for weighing compound.

Desiccator with Drierite indicating desiccant.

MATERIALS

Polyurethane resin, Parts A and B.

3M 251 epoxy, parts A and B.

Mold release.

RECOMMENDED PROPORTIONS (by weight)

Conap EN-2522, 50 parts A, 100 parts B.

Conap EN-2524, 42 parts A, 100 parts B.

Blend of EN-2524 and EN-2526.

EN-2524, part A 51 parts

EN-2524, part B 50 parts

EN-2526, part B 50 parts.

PROCEDURE FOR IMPREGNATION

The coils to be treated are dried 16 to 24 hours in the oven at 110° C, placed in a metal or glass container having a free space of about 4 to 6 inches over the units, and evacuated in the vacuum tank a minimum of 4 hours without heating.

A sufficient quantity of the polyurethane resin to ensure coverage of the coils by 1/2 inch is weighed in the recommended proportions in a metal or glass container and stirred thoroughly using a stirrer of metal,

PROCESS SPECIFICATION MC-102 (Continued)

glass, or non-cellulosic plastic. (Caution: In working with polyurethane resins, it is essential that containers and stirring implements be constructed of materials of minimum moisture content, since moisture causes bubbling of the resin. Paper, wood, and phenolic-cellulosic materials are to be avoided.) The time spent in stirring should be kept to a minimum (about 3 minutes) because of the short pot life of the mixed resin.

The mixed compound without prior degassing is introduced to the vacuum chamber by means of a disposable polyethylene tube. Degassing of the compound will occur as the material enters the vacuum chamber, and the rate of admission should be controlled to avoid excessive foaming. The time required to cover the coils in the container should be kept to a minimum, again because of the short pot life, and should not exceed 15 minutes.

After the units are covered, the flow of resin is cut off and vacuum is continued for about 5 minutes to further degas the resin. Finally, the vacuum pump is shut off and air is admitted slowly into the system until the pressure reaches atmospheric. The coils are allowed to soak in the resin for about 40 minutes, during which time the resin gradually increases in viscosity. When the resin has thickened sufficiently to prevent excessive drainage from the coil edges, the coils are withdrawn, excess resin allowed to drain off, and curing is accomplished at room temperature.

After 16 to 24 hours at approximately 25 degrees C, the resin will have cured sufficiently for handling the coils. At this time the coils are transferred to the dessicator and left therein for 6 days to effect complete cure.

PROCESS SPECIFICATION MC-102 (Continued)

PROCEDURE FOR ENCAPSULATION

The impregnated coils are positioned in suitable molds, which have been treated with mold release, and are placed in the oven for 2 to 4 hours at 70 degrees C.

3M Epoxy, 251 Parts A and B, is heated to 70 degrees C and each part is stirred to disperse evenly the filler. A sufficient quantity is weighed in the ratio 1 part A to 1 part B, mixed thoroughly, and degassed under 2 to 5 Torr vacuum until major bubbling subsides. The molds are half filled with the resin, evacuated for about 5 minutes, then filled with additional resin and evacuated for 5 to 10 minutes. Curing is accomplished in 16 hours at 65 degrees C, followed by 4 hours at 75 degrees C.

Corona tests were made on the coils at room temperature before impregnation, and at both room and elevated temperatures after impregnation and after potting. The test results of three coils (total layer insulation of 12.8 mils, 25.6 mils, and 38.4 mils) impregnated with Conap EN-2522 and then potted with 3M-251 Epoxy are given in Table 17.

TABLE 17

RESULTS OF CORONA TESTS ON SPECIMEN COILS IMPREGNATED WITH
CONAP EN-2522 AND ENCAPSULATED IN 3M #251 FILLED EPOXY

17A - COIL #81 - 2 Layers #25 HML Wire

Interlayer insulation - 2 mil Kapton H interleaved with 1.2 mil Pellon
#7200 unidirectional polyester fiber mat, 4 layers, total thickness
12.8 mils. Wire wound over Kapton.

Impregnated with Conap EN-2522 unfilled polyurethane and potted
in 3M #251 epoxy.

	CIV/CEV (Volts)	Average CIV/ CEV Stress (Volts/Mil)
Before Impregnation	1680/1550	131/121
After Impregnation, 3 days cure	3600/3540	281/276
After Impregnation, 7 days cure	3760/3700	294/290
After 30 minutes at 50 degrees C	4600/4400	359/344
After 60 minutes at 70 degrees C	4040/3900	315/305
Cooled to Room Temperature	3800/3700	297/290
Retested before Potting (11 days cure)	4000/3900	312/304
After Potting, tested at 70°C	>6000*	>470*
After Cooling, 24 hrs. room temp.	6400/6000	500/470
Retested after 5 days room temp.	>6400*	>500*

* Where "greater than" (>) sign appears, voltages were
limited to prevent possible breakdown of specimens,
which were to be used for further tests.

TABLE 17 (Continued)

17B - COIL #82 - 2 Layers #25 HML Wire

Interlayer Insulation - 2 mil Kapton H interleaved with 1.2 mil Pellon #7200 unidirectional polyester fiber mat, total thickness 25.6 mils. Wire wound over Kapton.

Impregnated with Conap EN-2522 unfilled polyurethane and potted in 3M #251 epoxy.

	CIV/CEV (Volts)	Average CIV/ CEV Stress (Volts/Mil)
Before Impregnating	2300/2280	90/89
After Impregnating, 4 days cure	>6400	> 250
After Potting, tested at 70°C	>6400	> 250
Cooling 70°C to room temp.	>6400	> 250
Tested at room temperature	7800/7750	305/303

17C - COIL #84 - 2 Layers #23 HML Wire

Interlayer insulation - 2 mil Kapton H interleaved with 1.2 mil Pellon #7200, unidirectional polyester fiber mat, total insulation thickness 38.4 mils. Wire wound over Kapton.

Impregnated with Conap EN-2522 unfilled polyurethane and potted in 3M #251 epoxy.

	CIV/CEV (Volts)	Average CIV/ CEV Stress (Volts/Mil)
Before Impregnating	2700/2550	70/66
After Impregnating, 4 days cure	5800 (Inter-mittent)	149
After Potting tested at 70°C	> 6400	> 166
70°C to approximately 40°C	> 6400	> 166
At approximately 40°C	6400/6000	166/156
Tested at room temperature	5700/5600	148/146

The results given in Table 17 show an improvement of corona inception voltage of the impregnated coils by factors of 2.24 to 2.80 compared with the unimpregnated coil with average CIV stresses ranging from 149 volts per mil for 38.4 mils of insulation to 297 volts per mil for 12.8 mils of insulation.

Two of the coils (#81 and #82) showed an improvement in corona inception voltage upon potting, with final average CIV stresses of more than 500 volts per mil for 12.8 mils of insulation and 305 volts per mil for 25.6 mils, representing improvements in average CIV stress by factors of 3.8 and 3.4 compared with the unimpregnated coils. The third coil (#84) exhibited the same CIV before and after potting.

In order to obtain information on how the corona inception voltages of the specimen coils were affected by temperature cycling, the coils in Table 16 were subjected to 5 temperature cycles of one hour at 100°C, followed by cooling to 25°C. The CIV/CEV was measured at both extremes of temperature. The data presented in Table 18, are difficult to interpret because of the inconsistent results. Coil #82 with 25.6 mils of insulation maintained high CIV's throughout the cycling. Coil #81, 12.8 mils insulation, had a lower CIV at 100°C than at room temperature, and changed in only a minor degree over the 5 cycles. Coil #84, 38.4 mils of insulation, had the reverse characteristic of Coil #81; it had a lower CIV at 25°C than at 100°C, and the room temperature CIV/CEV was progressively degraded while the 100°C CIV/CEV remained high over the 5 cycles.

TABLE 18

RESULTS OF TEMPERATURE CYCLING
ON THE CIV/CEV LEVEL OF COILS IMPREGNATED WITH
POLYURETHANE AND POTTED IN RIGID FILLED EPOXY

Layer Insulation: Kapton H Film and Polyester Web
 Impregnant: Conap EN-2522
 Encapsulant: 3M Compound #251
 Temperature Cycle: 1 Hour at 100°C followed by
 cooling to room temperature

Cycle Number	Temperature Of Test	CIV/CEV (Volts)		
		Coil 81 Ins. 12.8 mils	Coil 82 Ins. 25.6 mils	Coil 84 Ins. 38.4 mils
Before Cycling	25°C	6720/6530	7800/7600	7210/6630
1	100°C	- No Test	Data Taken -	
1	25°C	3600/2700	6700/6600	5640/5300
2	100°C	3800/3600	> 6400	> 6400
2	25°C	6400/5000	> 6400	5200/4960
3	100°C	2900/2720	> 6400	> 6400
3	25°C	6400/5600	6400/6200	4400/3540
4	100°C	3000/2900	> 6400	> 6400
4	25°C	6100/5600	> 6400	3940/3740
5	100°C	2940/2900	> 6400	> 6400
5	25°C	5600/5500	6400/5800	3300/3200
		AVERAGE	CIV/CEV STRESS	(Volts/Mil)
5	100°C	230/227	> 250	> 166
5	25°C	437/430	250/226	86/83

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5.4.4. Two-Stage Process Using Long Pot Life Blend Of Polyurethanes As Impregnant

In connection with the two-stage process of encapsulation, efforts were made to develop a room temperature curing polyurethane with longer pot life than that of commercially available compounds, which have a maximum pot life of 30 to 60 minutes. Longer pot life is desirable not only from the resin handling standpoint, but also because the longer period of time in which the resin remains in the liquid state affords a longer time during which the process of impregnation takes place.

A study of vendor's literature, including viscosity vs time curves for catalyzed resins, revealed that Conap EN-2526, a polyurethane having the same isocyanate base as the EN-2522 resin, has a pot life of 3 hours at 25 degrees C. Pot life is here defined as the time after mixing required for a 1 pound mass to reach a viscosity of 2000 centipoises. The EN-2526 resin is ordinarily cured at 60 degrees C and yields a polymer of hardness 80 Shore D having poor thermal shock properties. An experiment was conducted to determine the feasibility of blending the EN-2526 resin with an elastomeric resin to obtain room temperature cure with flexibility and increased pot life.

The blend was formulated as follows:

- Conap EN-2524 Part A, 51 parts by weight
- Conap EN-2524 Part B, 50 parts by weight
- Conap EN-2526 Part B, 50 parts by weight.

A test piece was poured into a mold and cured overnight at room temperature. After this period of time the material was slightly tacky, but could be removed from the mold. After another 24 hours the tackiness disappeared and the material had elastomeric properties similar to Conap EN-2522. It is believed that at least a week is required for complete cure, as in the case of EN-2524 and EN-2522.

In order to make a comparison between Conap EN-2524 polyurethane and the blend of equal parts of EN-2524 and EN-2526, four coils were wound, impregnated, and encapsulated in accordance with Process Specification MC-102 using impregnant EN-2524 for one set of two coils and the blend of EN-2524 and EN-2526 for the other set of two coils. For the blend, Process Specification MC-102 was modified extending the soak period to 2 1/4 hours because of the slower cure of the material.

Details of construction and processing are given in Table 19.

The coils were tested for corona before impregnation, after impregnation but before encapsulation, and after encapsulation. Following encapsulation, the coils were aged thermally in an oven at 100 degrees C and tested for corona at 100 degrees C and at room temperature after various periods of time. The results are recorded in Table 19.

The changes in corona inception voltage accompanying thermal aging of impregnated and encapsulated coils are shown graphically in Figures 13 and 14. Figure 13 is a plot of room temperature corona inception voltage vs time aged at 100 degrees C for coils having insulation thicknesses of 3.2 and 6.4 mils, impregnated with Conap EN-2524 polyurethane or a blend of EN-2524 and EN-2526. Figure 14 is a similar plot showing corona inception voltage measured at 100 degrees C.

Discussion

Tests on coils impregnated with polyurethane and potted in rigid epoxy have shown that it is possible to obtain very high average corona inception voltage stresses, up to 1000 volts per mil for 3.2 mils of insulation, immediately after potting. However, when the coils are subjected to elevated temperature, a drop in corona inception voltage occurs during the first few hours of heating. The cause of this change is believed to be a post-curing of the resins at the higher temperature, giving rise to mechanical stresses which create minute voids within the insulation. Following the initial drop in corona inception voltage, the tests indicate that a levelling off of the corona inception voltage occurs and the CIV remains approximately constant during subsequent periods of thermal aging.

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TABLE 19

CIV/CEV OF SPECIMEN COILS AFTER THERMAL AGING
(Layer Insulation: 2 Mil Kapton H Interleaved With 1.2 Mil Polyester Web)

Coil Number		85	90	89	86
Insulation Thickness (Inches)		.0032	.0064	.0032	.0064
Impregnant		EN-2524	EN-2524	Blend	Blend
Encapsulant		3M-251	3M-251	3M-251	3M-251
CIV/CEV (Volts)					
Before Impregnation		1020/800	1410/1250	1130/800	1450/1180
Before Encapsulation		> 3000	2650/2480	> 3200	> 3200
After Encapsulation		> 3200	> 3200	> 3200	2850/2400
After Thermal Aging					
Hours at 100° C	Temperature Of Test				
3	100° C	1730/1650	3150/3000	1870/1700	2250/2200
3	Room	2300/1570	3700/3600	---	---
6	100° C	1800/1750	> 3200	1650/1580	2180/2120
9	100° C	1850/1780	> 3200	---	---
9	Room	2300/1770	3400/2850	---	---
12	100° C	2100/1960	2470/2430	---	---
15	100° C	1870/1720	2520/2480	---	---
22	100° C	---	---	1800/1630	2380/2300
22	Room	---	---	1650/1160	2340/2170
31	100° C	1920/1800	2580/2480	---	---
31	Room	2220/2050	2200/1950	---	---
41	100° C	---	---	1750/1670	2300/2280
41	Room	---	---	1700/1210	2600/2520
50	100° C	1720/1700	2500/2480	---	---
50	Room	2270/2000	2100/1980	---	---

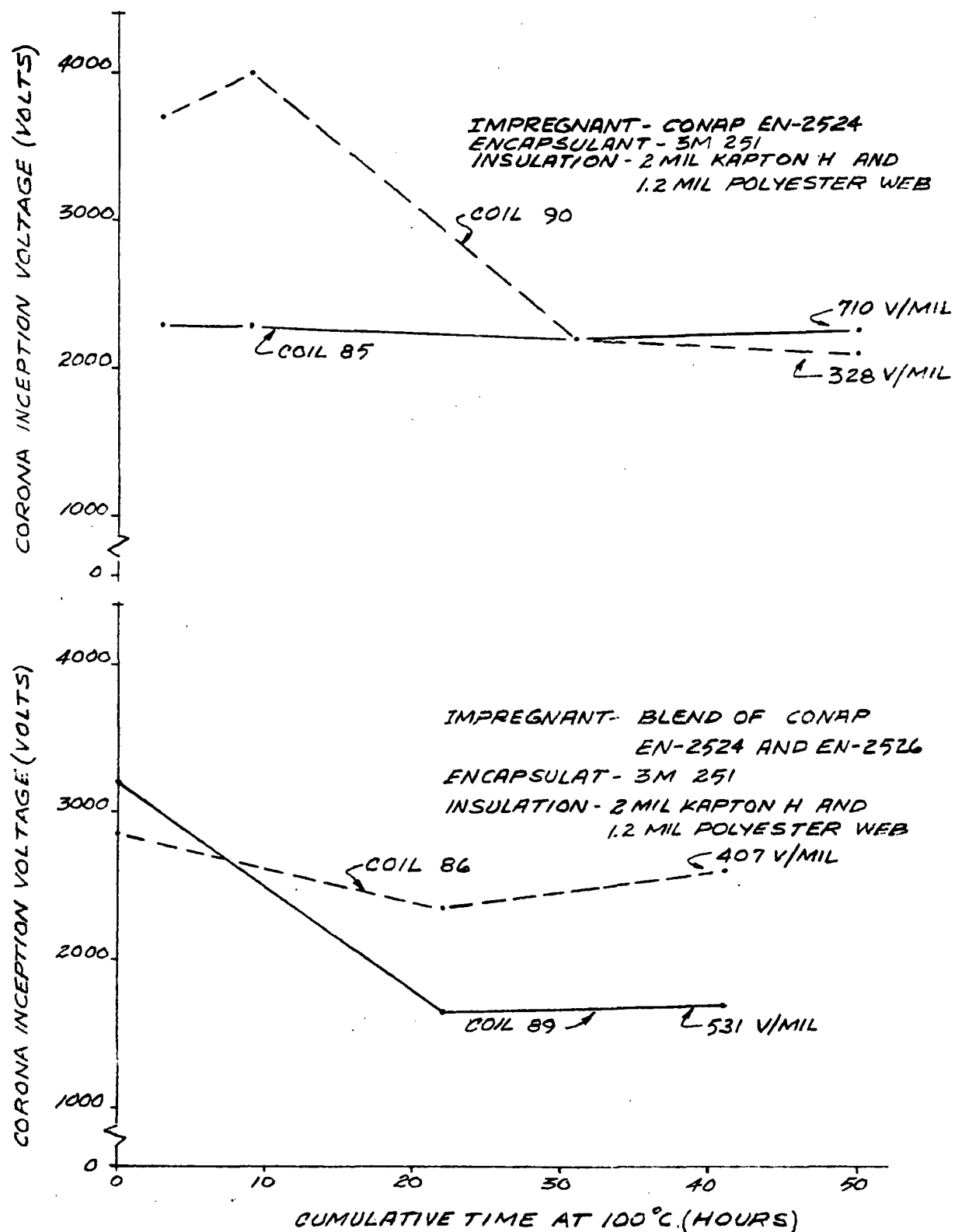


FIGURE 13

ROOM TEMPERATURE CIV OF COILS 85, 90, 89 & 86 AFTER AGING AT 100°C

(—— 0.0032 INCHES OF LAYER INSULATION)
 (--- 0.0064 INCHES OF LAYER INSULATION)

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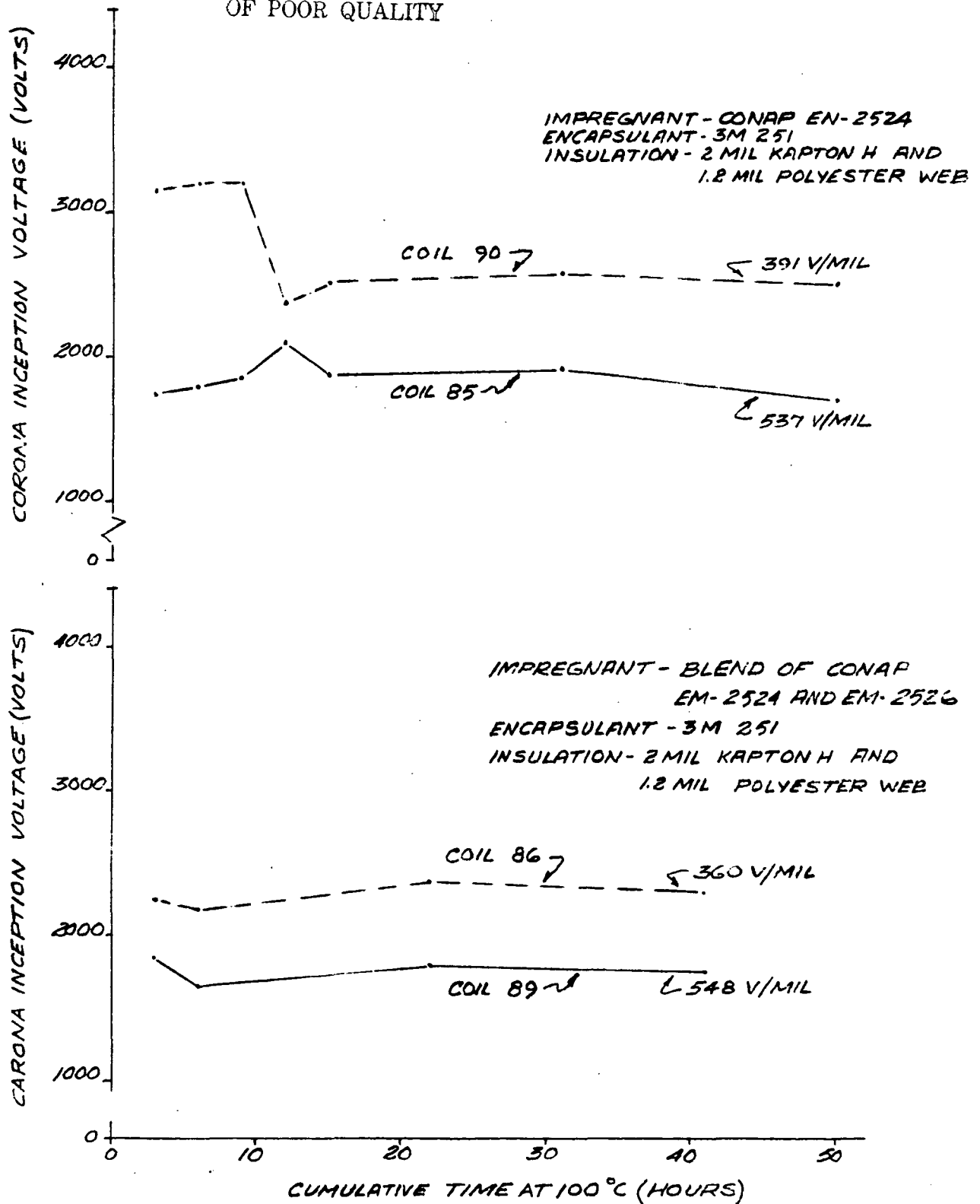


FIGURE 14

100 DEG. C. CIV OF COILS 85, 90, 89 & 86 AFTER AGING AT 100°C

(—— 0.0032 INCHES OF LAYER INSULATION)
 (--- 0.0064 INCHES OF LAYER INSULATION)

Average CIV stresses attained in 40 to 50 hours aging at 100 degrees C were in excess of 500 volts per mil for 3.2 mils of insulation and more than 300 volts per mil for 6.4 mils.

The change in CIV as a result of thermal aging can be minimized by post curing the potted coils at a temperature at least as high as the maximum expected operating temperature for a period of time sufficient to stabilize the resins. An overnight post-cure should be sufficient to accomplish this result.

No significant differences in corona inception voltages due to thermal aging were observed between the coils impregnated in EN-2524 and the blend of EN-2524 and EN-2526. The blend would probably have advantages in coils with larger traverse, since the longer pot life affords more time for the resin to penetrate the winding.

5.4.5 Additional Corona Tests On Encapsulated Coils With Polyurethane Impregnant After Thermal Aging

Coils 81, 82, and 84 (See Table 18 for description) were subjected to additional thermal aging periods up to 42 hours. The final corona tests on coils impregnated in polyurethanes, encapsulated in Scotchcast 251, and aged at 100 degrees C are presented in Table 20. Also included in Table 20 for comparative purpose are the final test results for the four coils discussed in Section 5.4.4. The degradation in CIV caused by thermal aging in several instances amounts to 50% of the original CIV.

Minimum CIV/CEV for coils 89, 90, 81, 82, 84 measured at 25 degrees C or 100 degrees C after thermal aging are presented in Table 21. A comparison of the test results in Table 21 with the test results for unimpregnated coils using Kapton insulation in Table 15A shows that the improvement due to encapsulation is between 50% and 100%, except for coil 84, which shows only a 20% improvement.

TABLE 20

CIV/CEV VOLTAGES OF IMPREGNATED AND ENCAPSULATED COILS
AFTER THERMAL AGING AT 100 DEGREES C

Coil Number	Insulation Thickness (Mils)	Impregnant	CIV/CEV (Volts)			Hours Aged
			Before Aging	After Aging	At 100° C	
			25°	25°	100°	
85	3.2	2524	> 3200	2270/2000	1720/1700	50
89	3.2	2524/26	> 3200	1700/1210	1750/1670	41
90	6.4	2524	> 3200	2100/1980	2500/2480	50
86	6.4	2524/26	2850/2400	2600/2520	2300/2280	41
81	12.8	2522	6720/6530	4600/4540	3260/3160	42
82	25.6	2522	7800/7750	6200/6000	3740/3640	42
84	38.4	2522	7200/6630	3380/3260	> 8000	42
Interlayer Insulation: .002 Inch Kapton-H Interleaved With .0012 Inch Pellon 7200 Polyester Web						
Encapsulant: 3M, #251						

TABLE 21

MINIMUM CIV/CEV AND AVERAGE CIV/CEV STRESS FOR POLYURETHANE
IMPREGNATED-EPOXY ENCAPSULATED COILS AFTER AGING AT 100 DEGREES C

Coil Number	Insulation Thickness (.002 In. Kapton + .0012 In. Polyester Web)	Minimum CIV/CEV And Average CIV/CEV Stress At 25 Degrees And 100 Degrees C	
		Volts	Volts Per Mil
89	3.2	1700/1210	531/378
90	6.4	2100/1980	328/310
81	12.8	3260/3160	255/247
82	25.6	3740/3640	146/142
84	38.4	3380/3260	88/85

5.4.6 Single-Stage Process For The Impregnation/ Encapsulation Of Transformer Windings

In view of the change in CIV due to the aging of coils impregnated with polyurethane and encapsulated in rigid epoxy, experiments were conducted to evaluate coils impregnated and encapsulated in a single stage operation using low weight loss epoxy.

On referring to Section 7.1.2 in which essential properties of a number of resins are discussed, it will be seen that Scotchcast 251 exhibits very low weight loss, a low viscosity of under 300 centipoises for a period of two hours at 77 degrees C, low coefficient of thermal expansion, and fair thermal shock resistance.

The experiments were conducted on specimen coils wound as previously described (Section 5.4.1) using Number 25 HML wire with layer insulation consisting of polyimide film (Kapton H) interleaved with oriented non-woven polyester web (Pellon Corp. Number 7200) with total insulation thicknesses from 3.2 to 32.0 mils.

The coils were impregnated and encapsulated in polypropylene molds in accordance with Process Specification 103, (Section 7.4.2).

5.4.7 Corona Tests On Coils Impregnated And Encapsulated
In Scotchcast 251 After Thermal Aging

After encapsulating and removing from the mold, the coils were aged for various periods of time at 100 degrees C. Two coils were aged at 100 and 120 degrees C. Results of corona tests performed at 25 degrees C and 100 degrees C are shown in Table 22

All of the coils, except #94, showed high CIV/CEV at the completion of the tests. Number 94 had a low CIV/CEV after potting and showed excessive shrinkage. It was found that this unit had inadvertently been cured at a temperature of 80 degrees C instead of 68 degrees C. The CIV/CEV at 100 degrees C were somewhat lower than the CIV/CEV measured at 25 degrees C.

The tests, which were designed to determine the capability of properly impregnated layer insulation as one element of the transformer, indicate that the epoxy impregnated polyimide film-polyester web combination can be stressed to 200 volts per mil for 32 mils of insulation, and as high as 700 volts per mil for 3.2 mils based on 90% of the minimum corona extinction voltages measured at 100 degrees C after aging.

5.5 Summary Of Results Of The Experimental Program

1. For the unimpregnated experimental coils, Kapton H and Nomex 410 show essentially the same CIV which is higher than the CIV of the other insulations tested. Kapton H is preferred because of its more compact winding characteristics.
2. Calculated voltage gradients can provide a valuable tool in the design of unimpregnated coils. Within the range of insulation thicknesses tested, the corona inception voltage gradient on the surface of the AWG #25 wire was found to be 162.4 volts per mil with a deviation of plus or minus 3.3 percent. Additional experimental data is needed on wires of other sizes and on various insulation systems.

Coil Number	Insulation Thickness (Mils)	CIV/CEV AND AVERAGE CIV/CEV STRESS					Hrs./Temp °C
		Before Potting (Volts)	After Potting And Aging				
			Volts		(Volts/Mil)		
			25° C	100° C	25° C	100° C	
91	3.2	1000/890	> 5000	2900/2520	> 1550	906/788	40/100
97	3.2	880/800	> 5000	> 5000	> 1550	> 1550	3/100 +5/120
92	6.4	1500/1400	10000/9000	7000/6600	1560/1400	1090/1030	23/100
93	9.6	1750/1360	11000/10600	> 10000	1146/1100	> 1040	26/100
94	19.2	2600/2000	2300/1920	----	----	----	None
96	24.8	2250/2020	12000/11800	9600/6800	484/476	387/274	3/100 +5/120
95	32.0	3360/2320	11000/10800	9400/8000	334/338	263/250	16/100

TABLE 22

CIV/CEV AND AVERAGE CIV/CEV STRESS OF COILS ENCAPSULATED IN SCOTCHCAST 251 BEFORE AND AFTER AGING AT ELEVATED TEMPERATURE

All coils except #96 were insulated with interleaved .002 Kapton H and #7200 polyester web. Coil #96 was similarly insulated except that .005 Kapton was used.

3. Corona inception voltages in encapsulated coils were found to vary significantly with temperature.
4. Temperature cycling of encapsulated coils between 25 and 100 degrees C in many cases caused a degradation of corona inception voltage.
5. Best results on encapsulated coils were obtained using interleaved layers of Kapton H film and Pellon 7200 oriented non-woven polyester web as layer insulation and encapsulating under vacuum with Scotchcast 251 rigid filled epoxy.

6.0 THE OPEN-TO-SPACE TRANSFORMER

The advantages and limitations of the open-to-space type of transformer have been discussed in Section 4.1. In brief, this type of construction aims to take advantage of the excellent dielectric properties of the ultra-high vacuum of space by eliminating encapsulation or any other form of non-permeable enclosure. After a period of conditioning in high vacuum to remove moisture and absorbed gaseous products, the insulation is capable of sustaining very high voltages for extended periods of time.

6.1 Materials For Open-To-Space Transformers

The insulation used in the open transformer is of thermal Class H (180 degrees C) and is chosen from a group of materials of outstandingly low out-gassing characteristics, such as mica, fiberglass, and resins of the polyimide or silicone type.

A list of materials suitable for open construction transformers is given in Table 23. Vendors are listed in Appendix C.

Using the materials listed, the design engineer has a choice of two types of insulation systems, one of which is substantially all silicone, and the other substantially all polyimide. Compatible adhesives and impregnating varnishes will be silicone or polyimide, depending on the system chosen. Certain exceptions to the all-of-one kind construction may occur, such as the use of polyimide coated wire and silicone elastomer heat transfer compounds, which can be employed in either system.

Of the two systems, Kapton has a higher CIV, higher thermal conductivity (Reference 7) and yields a more compact winding which improves heat conductance. Isomica 4350, which is a mica paper-fiberglass laminate, silicone treated, has superior resistance to corona (References 8 and 9) and may have an advantage with respect to rate of initial outgassing.

TABLE 23
LIST OF MATERIALS FOR OPEN TYPE TRANSFORMERS

Magnet Wire

Polyimide double coated, HML, minimum size AWG-36.

Layer And Interwinding Insulation

Mica-fiberglass composite, silicone treated (Isomica 4350) - 5 mils, 8 mils

Polyimide film, 2 mils, 5 mils (Kapton H)

Aramid paper (Nomex 410) 2, 3, 5, 7, 10 mils.

Structural Materials (Coil Forms, Panels)

Woven fiberglass laminate, silicone treated (NEMA Grade G-7)
10 mils to 2.00 inches

Woven fiberglass laminate, polyimide treated, (Grade G-30),
31 to 125 mils.

Insulating Sleeving

Braided fiberglass, silicone treated

Braided fiberglass, untreated.

Tying And Lacing Tape

Aramid (Nomex), nylon treated.

Adhesives

Silicone resin (DC 2104)

Polyamide-imide (Kerimid 500)

Polyimide, fully cured (2080 D).

Conformal Coating

Silicone resin (DC-2104)

Polyimide, fully cured (2080 D).

Lead Wire

Polyimide-fluorocarbon film wrapped.

Core Materials

Nickel-Iron-Molybdenum alloy, 1 mil (Permalloy 80, etc.).

Ferrite, MN-100.

Heat Sink And Bonding Material

Filled silicone rubber compound (C6-1102).

6.2 Voltage Stress Design Criteria For Open-To-Space Transformers

Design criteria for voltage stresses in open transformers have been established based on results of corona tests made on specimen coils in air during the program. (See Section 5.3.3.)

Based on the experimental results, with an added safety factor, the following design criteria are recommended for creepage distance between windings in open transformers. (Table 24.)

TABLE 24 DESIGN CRITERIA FOR CREEPAGE DISTANCES IN OPEN-TO-SPACE TRANSFORMERS			
Wire Size (AWG)	Creepage Distance (Inches)	Maximum Voltage (Volts)	Average Voltage Stress (Volts/Mil)
18	1/8	4000	32
18	1/4	5000	20
18	3/8	6000	16
18	1/2	7000	14
30	1/8	2000	16
30	1/4	4000	16
30	3/8	6000	16
30	1/2	7000	14

Design criteria for maximum voltage stresses on Kapton and Isomica 4350 in open transformers have been established based on 90% of the corona extinction voltages and are presented in Table 25.

The design criteria of Table 25 have been determined from tests on coils wound with Number 25 AWG wire, and are considered conservative for this and larger wire sizes. For finer wires, additional experimental data are needed.

TABLE 25 DESIGN CRITERIA FOR KAPTON H FILM AND ISOMICA 4350 MICA- FIBERGLASS COMPOSITE IN OPEN-TO-SPACE TYPE TRANSFORMERS					
KAPTON H-FILM			ISOMICA 4350		
Thickness (Mils)	Maximum Voltage (Volts)	Average Voltage Stress (Volts/Mil)	Thickness (Mils)	Maximum Voltage (Volts)	Average Voltage Stress (Volts/Mil)
6	1000	167			
10	1200	120	10	850	85
20	1700	85	20	1300	65
30	2100	70	30	1700	57
40	2400	60	40	2100	52
50	2700	54	50	2400	48

6.3 Design Calculations And Test Results For Open Transformer, OM-2, Sub 6

The transformer requirements are as follows:

Primary	200 V
Secondary 1	1100 V @ 2.2A, 2420 VA
Secondary 2	1100 V @ 0.2A, 200 VA
Input Waveform	Square Wave
Frequency Limits	2 - 40 KHz
Efficiency	97% Minimum
Ambient Temperature Range	-55 to 85 degrees C
Weight	1 Kilogram Maximum
Construction	Open

6.3.1 Calculation of $A_c A_w$ Product and Selection of Core

A Permalloy 80, 1 mil, tape wound C - Core was selected because of this materials low loss characteristics. The operating frequency selected was 12 KHz; the maximum flux density selected was 5 KG and for these values the vendor's data gives a specific core loss of 18 w/lb under sinusoidal voltage excitation. As indicated in Section 4.2.1, lower specific core losses can be obtained for a given B_m product by increasing f and decreasing B_m . Unfortunately, the results given in Section 4.2.1 were not yet available at the time the designs and hardware development of the transformers listed in Table 1 were being finalized. However, transformer OM-2 Sub 7, which has the same requirements as OM-2 Sub 6, was designed and built to operate at the upper specified frequency limit of 40 KHz. Transformer OM-2 Sub 7 is described in Section 6.4.

The $A_c A_w$ product is determined by means of equation (3.5),

$$A_c A_w = \frac{(E_p I_p + E_{s1} I_{s1} + E_{s2} I_{s2}) J \times 10^5}{4 (FF) B_m f (SF)_c (SF)_w}$$

where the inverse current density J is initially assumed to be the same in each winding and given a value of 500 cir. mils/amp. (253.4×10^{-5} cm²/amp). Also, we have

$$\begin{aligned} E_{s2} I_{s2} &= \text{Secondary 2 volt - amps} = (1000) (0.2) = 200 \text{ VA} \\ E_{s1} I_{s1} &= \text{Secondary 1 volt-amps} = (1100) (2.2) = 2420 \text{ VA} \\ \text{Estimated losses for efficiency of } 98.5\% &= 40 \text{ W} \\ E_p I_p &= \text{Primary volt-amps} = (2420 + 200 + 40) = 2660 \text{ VA} \\ (FF) &= \text{Form factor for square wave} = 1 \\ B_m &= \text{Maximum flux density} = 5 \text{ KG} \\ f &= \text{Operating frequency} = 12 \text{ KHz} \\ (SF)_c &= \text{Space factor of Core} = 0.8 \\ (SF)_w &= \text{Space factor of window} = 0.2 \end{aligned}$$

$$A_c A_w = \frac{(2660 + 2420 + 200) (253.4 \times 10^{-5}) \times 10^5}{(4) (5) (12000) (0.8) (0.2)} = 34.8 \text{ cm}^4 = 0.84 \text{ in}^4$$

By referring to the vendors list of stock C - cores, it was found that Magnetics Inc. MC - 1389 core meets the above calculated $A_c A_w$ value and this core was selected for the design. Core MC -1389 has the following physical characteristics:

$$\begin{aligned} \text{Dimensions: } D &= 5/8 \text{ in; } E = 5/8 \text{ in} \\ F &= 7/8 \text{ in; } G = 2 \text{ } 3/4 \text{ in} \\ A_c &= \text{Cross - sectional area} = DXE = 0.39 \text{ in}^2 \\ A_w &= \text{Window area} = FXG = 2.41 \text{ in}^2 \\ A_c A_w &= 0.94 \text{ in}^4 \\ \text{Weight} &= 1 \text{ lb} \end{aligned}$$

The square cross section of the core insures minimum mean length of turn. The high ratio of window width to window height (i.e. a factor

of 3.1) will result in few layers of turns and also a relatively small space occupied by margins, and thus contributing to a good space factor.

6.3.2 Calculation of Number Of Turns, Wire Size

For this design a two coil construction is used. The winding arrangement of each coil is identical but electrically the primary windings are connected in parallel while both the secondary 1 and secondary 2 windings are series connected. The number of turns and wire size for each winding is determined as follows:

Primary

The number of primary turns is determined by the use of equation (3.1).

$$N_p = \frac{E_p \times 10^5}{4 (FF) B_m f A_c (SF)_c} = \frac{200 \times 10^5}{(4)(1)(5)(12000)(2.52)(0.8)} = 41$$

The maximum allowable diameter of the insulated primary wire is the ratio of primary winding width divided by the number of primary turns. The coil tube width is the difference between the core window width and the tube clearance. The primary winding width is found by subtracting the sum of the flange thicknesses and margins from the coil tube width. If the tube clearance is 1/8 in., each flange 1/16 in., and each margin 1/8 in, then for the MC -1389 core we have,

$$\text{Coil tube width} = 2 \frac{3}{4} - \frac{1}{8} = 2 \frac{5}{8} \text{ in}$$

$$\text{Primary winding width} = 2 \frac{5}{8} - 2(\frac{1}{16} + \frac{1}{8}) = 2 \frac{1}{4} \text{ in}$$

Thus,

$$\text{Max. insulated wire diameter} = \frac{2 \frac{1}{4}}{41} = 0.0549 \text{ in}$$

From the wire tables for a heavy film wire insulation, the wire size required is #16AWG, and the primary will consist of a single layer of 41 turns on each coil.

The primary volt-amps is 2660 VA and since the primary voltage is 200 V, then the primary current, I_p , is

$$I_p = \frac{2660 \text{ VA}}{200 \text{ V}} = 13.3 \text{ A}$$

Since the primary winding on each coil is connected in parallel, then the primary current in each parallel winding is $(13.3/2) = 6.65\text{A}$. From the wire tables the cross-sectional area of the bare # 16 AWG wire is 2580 cir. mils. Then by equation (3.6) the primary inverse current density is

$$J_p = \frac{A_p}{I_p} = \frac{2580 \text{ cir mils}}{6.65 \text{ A}} = 388 \text{ cir. mils/A}$$

Secondary 1

By the use of equation (3.1), the number of secondary 1 turns is

$$N_{S1} = \left(\frac{V_{S1}}{V_p} \right) N_p = \frac{1100 (41)}{200} = 226$$

The secondary 1 winding width per layer is the coil tube width less the flange thicknesses and margins. For $\frac{1}{4}$ in. margins we have

$$\text{Sec. 1 winding width} = 2 \frac{5}{8} - 2\left(\frac{1}{16} + \frac{1}{4}\right) = 2 \text{ in.}$$

The specified sec. 1 current is 2.2 A and so for an assumed inverse current density of 500 cir. mils/A, a bare wire cross-sectional area of $(500)(2.2) = 1100 \text{ cir. mils}$ is required. The wire size nearest

to this is #20 AWG which has a cross-sectional area of 1020 cir. mils. Hence, the inverse current density for sec. 1 is $(1020/2.2) = 463$ cir. mils/A.

The maximum diameter of #20 AWG wire with heavy film insulation is 0.351 in. The total sec. 1 winding width is $(226) (0.0351) \approx 7.93$ in. and the number of layers required is $(7.93 \text{ in.}/2 \text{ in./layer}) = 4$ layers. Thus, 2 layers, one of 56 turns, and one of 57 turns, is required for each coil and all layers are series connected.

Secondary 2

By equation (3.1), the number of secondary 2 turns is

$$N_{s2} = \left(\frac{V_{s2}}{V_P} \right) N_P = \left(\frac{1000}{200} \right) \times 41 = 205$$

The secondary 2 winding width per layer is the coil tube width less the margins and flanges. For $15/32$ in. margins and $1/16$ in. flanges, we have
 Sec. 2 winding width $= 2 \frac{5}{8} - 2(1/16 + 15/32) = 1 \frac{9}{16}$ in.

For a single layer of 102 turns on one coil and 103 turns on the other coil, the maximum allowable heavy film insulated wire is

$$\text{Max. insulated wire diameter} = \frac{2(1 \frac{9}{16})}{205} = 0.0152 \text{ in.}$$

This diameter corresponds to #28 AWG wire with a bare wire cross-sectional area of 159 cir. mils. Secondary 2 is to carry 0.2 A so the inverse current density is

$$J_{s2} = \frac{159}{0.2A} \text{ cir. mils} = 795 \text{ cir. mils/A}$$

6.3.3 Layer and Interwinding Insulation, Coil Build, Window Space Factor

Table 25 of Section 6.2 indicates that 10 mils of Kapton film would be adequate for the maximum interwinding voltage of 1100 volts

using AWG 25 wire or larger. In the actual design, advantage is taken of available space in the core window to achieve higher CIV than the design requirements without necessitating significant increase in the size of the core. The coil build-up is given in Table 26.

TABLE 26		
COIL BUILD-UP FOR EACH COIL OF TRANSFORMER QM-2, SUB 6		
Build Up Sequence	Incremental Build (in.)	Total Build (in.)
Tube Wall	0.055	0.055
Tube Wrapper (3X 0.002 in)	0.006	0.061
Primary # 16 HML	0.055	0.116
Primary Wrapper (4X 0.005 in.)	0.020	0.136
Shield	0.002	0.138
Shield Wrapper (16X 0.005 in.)	0.080	0.218
Sec. 1, Layer 1, #20 HML	0.035	0.253
Sec. 1, Layer 1 Wrapper (5X 0.002 in.)	0.010	0.263
Sec. 1, Layer 2, #20 HML	0.035	0.298
Sec. 1, Layer 2 Wrapper (6X 0.005 in.)	0.030	0.328
Sec. 2, #28 HML	0.015	0.343
Sec. 2 Wrapper (4X 0.005)	0.020	0.363

In calculating the $A_c A_w$ product in Section 6.3.1, a window space factor, $(SF)_w$, of 20% was assumed. Since $(SF)_w$ is the fraction of window area filled with bare conductor, then

$$(SF)_w = \frac{2N_p a_p + N_{S1} a_{S1} + N_{S2} a_{S2}}{A_w}$$

$$(SF)_w = \frac{2(41)(2.03 \times 10^{-3} \text{ in.}^2) + (226)(0.804 \times 10^{-3} \text{ in.}^2) + (205)(0.125 \times 10^{-3} \text{ in.}^2)}{(2.41 \text{ in}^2)}$$

$$\therefore (SF)_w = 0.16$$

Thus, a window space factor of 16% is obtained for the coils of the OM-2, Sub 6 transformer.

6.3.4 Calculation of Losses And Efficiency

Core Loss

According to the vendor's data, the specific core loss is 18 watts per pound for a Permalloy 80, 1 mil, tape wound C-Core under sinusoidal voltage excitation 12 KHz and 5 KG. Specific core loss data for this set of conditions under square wave excitation does not exist, so the sinusoidal excitation value will be used. The MC-1389 core weighs 1 pound, so the core loss is 18 watts.

Conductor (I^2R) Loss

The conductor, I^2R , or 'copper' loss for each winding is determined by the use of equations (3.7) through (3.11) and the results given in Table 26. The total computed I^2R loss and the values used to obtain this total loss are given in Table 27. The inside dimensions of the coil table are 21/32 in. x 23/32 in.

TABLE 27			
CONDUCTOR (I^2R) LOSSES FOR TRANSFORMER OM-2, SUB 6			
	Primary	Secondary 1	Secondary 2
Average Number of turns/Coil	41	113	102.5
MLT/ Coil (in.)	3.31	4.37	4.86
Winding Length/Coil (ft.)	11.31	40.97	41.51
Wire Size (AWG)	#16	#20	#28
DC Resistance (ohms) per ft	0.00402	0.0101	0.0653
DC Resistance @ 20°C (ohms)	0.0227(1)	0.828(2)	5.42(2)
Current (A)	13.3	2.2	0.2
I^2R loss @ 20°C (watts)	4.02	4.01	0.22
Total I^2R Loss @ 20°C = 4.02 + 4.01 + 0.22 = 8.3 watts			
(1) Two coils in parallel.			
(2) Two coils in series.			

Efficiency

The computed efficiency using equation (3.12) is

$$\eta = \frac{P_{out}}{P_{out} + P_T} \times 100 = \frac{2620 \times 100}{2620 + 18 + 8.3} = 99.0\% @ 20^\circ \text{ C.}$$

6.3.5 Calculation of Temperature Rise

The procedures given in Section 3.6 are used to calculate the temperature rise. As a first approximation it is assumed that the temperature of each winding is 100°C and the resistance and I^2R losses for the windings are computed for this temperature. Equation (3.9) is used to determine the factor by which the resistance, and thus the I^2R losses, in Table 27 must be multiplied by. This factor is

$$\frac{R @ 100^\circ\text{C}}{R @ 20^\circ\text{C}} = \frac{234.5 + 100}{234.5 + 20} = 1.314$$

In the second calculation of the temperature rise, the temperature rises calculated in the first approximation are utilized to determine the temperature of each winding. These new temperature values, along with equation (3.9), are then used to determine the resistance and I^2R loss of each winding.

Two copper strips, 0.02 inches thick, are bonded to the core in contact with the edges of the laminations to improve the conduction of heat. The layer and interwinding insulation used in the coil is either 2 or 5 mil Kapton H film. The thermal conductivity, K , of both the Kapton H film and the ML wire insulation is arbitrarily derated to $0.003 \left(\frac{\text{watts} \times \text{in.}}{\text{in.}^2^\circ\text{C}} \right)$ to allow for winding interface.

The coil dimensions which are pertinent to the heat conduction process are calculated layer by layer and are recorded in Table 28.

In this table, the heat path, $\mathbf{X}$, includes only the insulation and not the copper wire since the thermal conductivity of copper is so much greater than that of the insulation. The mean length of insulation is computed in the same manner as the winding mean length of turn, and accordingly, equations (3.10) and (3.11) are used. The winding width is that determined in Section 6.3.2. The mean surface area perpendicular to the heat path is the product of the mean length of insulation times the winding width.

In table 29 the heat path, $\mathbf{X}$, and the mean surface area, A , along with the thermal conductivity, K , are used to compute the thermal resistance, $\mathbf{X}/KA$. The values of $\mathbf{X}$ and A for items 1 through 6 are taken from Table 28. The heat input, Q , at various points is the successive addition of heat due to the I^2R and core losses. In all items, except item 8, the incremental change in temperature, ΔT , is the product of the heat input and the thermal resistance. The reason for the exception for item 8, plus all other calculations for items 7 through 12, are given in the Notes following Table 29. The total ΔT is the sum of the incremental ΔT 's from the heat sink to the point under consideration.

TABLE 28

DIMENSIONAL DATA FOR EACH COIL OF TRANSFORMER OM-2 SUB 6

Material	Thickness (in)	Heat Path (in)	Total Build (in)	Mean length of Insulation (in)	Winding Width (in)	Mean Surface Area (in) ²
Tube Wall	0.055	0.055	0.055	2.92	2 $\frac{1}{4}$	6.58
Tube Wrapper (3 x 0.002 in)	0.006	0.0079	0.061	3.12	2 $\frac{1}{4}$	7.02
Pri. Wire Insulation	0.00185		0.063			
Pri. Bare Wire Dia. (#16)	0.0508		0.114			
Pri. Wire Insulation	0.00185	0.0219	0.116	3.54	2	7.08
Pri. Wrapper (4 x 0.005 in)	0.020		0.136			
Shield	0.002		0.138			
Shield Wrapper (16 x 0.005 in)	0.080	0.0816	0.218	3.87	2	7.74
Sec. 1, Layer 1 Wire Ins.	0.00155		0.219			
Sec. 1, Layer 1 Bare Wire Dia. (#20)	0.0320		0.251			
Sec. 1, Layer 1 Wire Ins.	0.00155	0.0131	0.253	4.38	2	8.76
Sec. 1, Layer 1 Wrapper (5 x 0.002 in)	0.010		0.263			
Sec. 1, Layer 2 Wire Ins.	0.00155		0.264			
Sec. 1, Layer 2 Bare Wire Dia. (#20)	0.0320	0.0326	0.296	4.69	1 9/16	7.34
Sec. 1, Layer 2 Wire Ins.	0.00155		0.298			
Sec. 1, Layer 2 Wrapper (6 x 0.005 in)	0.030		0.328			
Sec. 2, Wire Ins.	0.00105		0.329			

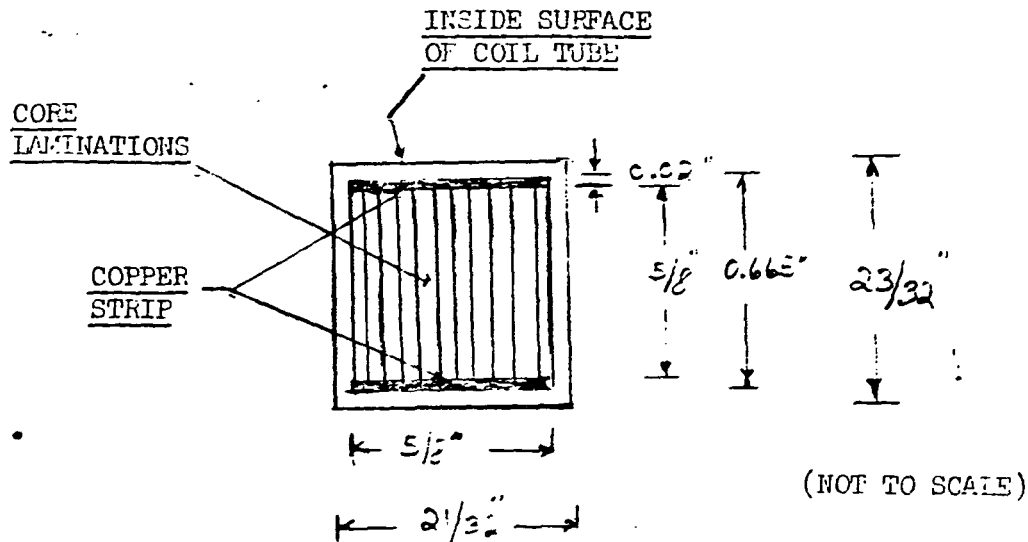
TABLE 29

CALCULATION OF TEMPERATURE FOR TRANSFORMER OM-2, SUB 6

Heat Conduction Path	X (in.)	K watts in. in 2 °C	A (in. ²)	X/KA (°C/watt)	Q @ 100°C (watts)	ΔT (°C)	ΔT Total (°C)
1. Sec. 2 to Sec. 1, Layer 2 Add Loss of Sec. 1, Layer	0.0326	0.003	7.34	1.48	0.145 1.32	0.22	55.3
2. Sec. 1, Layer 2 to Sec. 1, Layer 1 Add Loss of Sec. 1, Layer 1	0.0131	0.003	8.76	0.50	1.47 1.32	0.73	55.1
3. Sec. 1, Layer 1 to Shield	0.0816	0.003	7.74	3.51	2.79	9.79	54.4
4. Shield to Primary Add Pri. Loss	0.0219	0.003	7.08	1.03	2.79 2.64	2.87	44.6
5. Primary to Tube	0.0079	0.003	7.02	0.38	5.43	2.04	41.7
6. Tube Wall	0.055	0.008	6.58	1.04	5.43	5.65	39.7
7. Tube-Core Interface	0.021	0.008	6.00	0.44	5.43	2.38	34.0
8. Core Portion Under $\frac{1}{2}$ of Coil	1.125	1.244	0.42	2.17	4.92	5.34	31.6
9. Core-Coil to Area under Bracket				1.88	6.07	11.41	26.3
10. Core Portion Under Bracket	0.156	0.702	0.63	0.35	7.22	2.55	14.9
11. Core-Bracket Interface	0.01	0.008	0.92	1.36	7.22	9.82	12.3
12. Bracket to Heat Sink		5.5		0.35	7.22	2.51	2.5

NOTES ON TABLE 29

Item 7: Tube-Core Interface (Interface Filled with Sylgard 183).



$$X = \frac{1}{2} \left[\frac{(23/32 - 0.665)}{2} + \frac{(21/32 - 5/8)}{2} \right] = \frac{1}{2} [0.027 + 0.016] = 0.021 \text{ in.}$$

$$K = 0.008 \frac{\text{watt in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\text{Mean Length of Ins.} = \frac{2(23/32 + 21/32) + 2(5/8 + 0.665)}{2} = 2.665 \text{ in.}$$

$$\text{Winding Width} = 2 \frac{1}{4} \text{ in.}$$

$$\text{Area} = A = (2.665)(2 \frac{1}{4}) = 6.00 \text{ in.}^2$$

$$\frac{X}{KA} = \frac{0.021}{(0.008)(6.00)} = 0.438 \text{ } ^\circ\text{C/watt}$$

$$Q @ 100^\circ\text{C (Coil Loss)} = 5.43 \text{ watts}$$

$$\Delta T = \left(\frac{X}{KA} \right) Q = (0.438)(5.17) = 2.38 \text{ } ^\circ\text{C}$$

(Notes on Table 29, Cont.)

Item 8: Core Portion Under $\frac{1}{2}$ Coil

$$X = \frac{1}{2} \text{ primary winding width} = \frac{2\frac{1}{4}}{2} = 1\frac{1}{8} \text{ in.}$$

$$K = \text{Thermal conductivity of } 5/8 \text{ in. stack of Permalloy 80 with two } 0.02 \text{ in. copper laminations; Heat flow parallel to laminations. (See Table 2)} \\ = 1.244 \frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$A = \text{Cross sectional area of core and copper laminations} \\ = (5/8) (5/8 + 0.02) = 0.416 \text{ in.}^2$$

$$\frac{X}{KA} = 2.17 \text{ } ^\circ\text{C/watt}$$

Mean Magnetic Path Length = MMPL

$$\text{MMPL} = \frac{2(F + G) + 2(F + G) + 4 \left[\frac{2\pi E}{4} \right]}{2} = 2(F + G) + \pi E$$

$$F = 7/8 \text{ in.}; G = 2\frac{3}{4} \text{ in.}; E = 5/8 \text{ in.}$$

$$\text{MMPL} = 2(7/8 + 2\frac{3}{4}) + \pi(5/8) = 9.213 \text{ in.}$$

$$\text{Core losses for } 1\frac{1}{8} \text{ in. of core} = \frac{1\frac{1}{8}}{9.213} \times 18 \text{ watts} = 2.2 \text{ watts}$$

$$Q = \frac{1}{2} \text{ Coil } I^2R \text{ loss @ } 100^\circ\text{C} = \frac{5.43}{2} = 2.72 \text{ watts}$$

$$I^2R \text{ loss} + \text{Core loss} = 2.72 + 2.20 + 4.92 \text{ watts}$$

I^2R loss is uniformly added and core loss is self-generated so

$$\frac{Q}{2} = \frac{4.92}{2} = 2.46 \text{ watts}$$

$$\Delta T = \left(\frac{X}{KA} \right) \left(\frac{Q}{2} \right) = (2.17) (2.46) = 5.34^\circ\text{C}$$

(Notes on Table 29, Cont.)

Item 9: Core-Coil to Area Under Bracket

The bracket contacts only 3/8 in. of the 5/8 in. core stack, giving two heat flow paths through the core, as shown in Figure 15. Paths AB and DE are parallel to the laminations and path BC is perpendicular. AB and BC are in series, and ABC is in parallel with DE.

Path AB:

$$X = \left(2 \frac{3/4 - 2\frac{1}{4}}{4} \right) + \frac{2\pi}{4} \left(\frac{5/8 - 3/8}{2} \right) + \frac{1}{4} (7/8) = 0.665 \text{ in.}$$

$$K = 1.244 \frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$A = \left(\frac{1}{4} \right) \left[5/8 + 2(0.02) \right] = 0.166 \text{ in.}^2$$

$$\left(\frac{X}{KA} \right)_{AB} = 3.22 \text{ } ^\circ\text{C/watt}$$

Path BC:

$$X = \frac{\left(\frac{1}{4} \right)}{2} + \frac{(3/8)}{2} = 0.313 \text{ in}^2$$

$$K = \text{Thermal conductivity of } 5/8 \text{ in. stacks of Permalloy 80 with two } 0.02 \text{ in. copper laminations; Heat flow perpendicular to laminations (See Table 2)} \\ = 0.620 \frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$A = \left(\frac{7/8}{2} \right) \left[5/8 + 2(0.02) \right] = 0.291 \text{ in.}^2$$

$$\left(\frac{X}{KA} \right)_{BC} = 1.73 \text{ } ^\circ\text{C}$$

Path AB and BC in Series:

$$\left(\frac{X}{KA} \right)_{AC} = \left(\frac{X}{KA} \right)_{AB} + \left(\frac{X}{KA} \right)_{BC} = 3.22 + 1.73 = 4.95 \text{ } ^\circ\text{C/watt}$$

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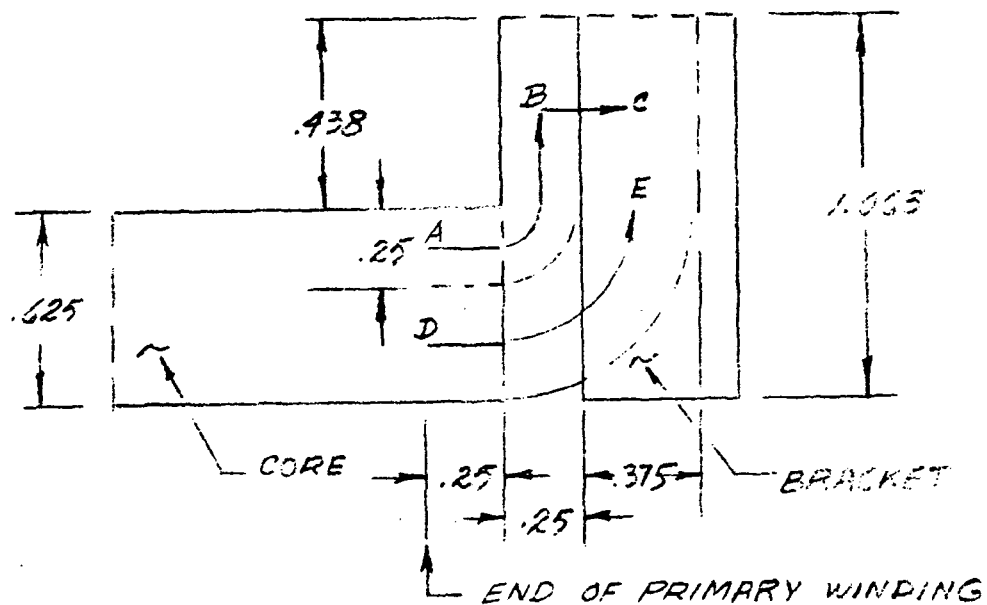


FIGURE 15

QUARTER SECTION OF CORE SHOWING
HEAT FLOW PATHS

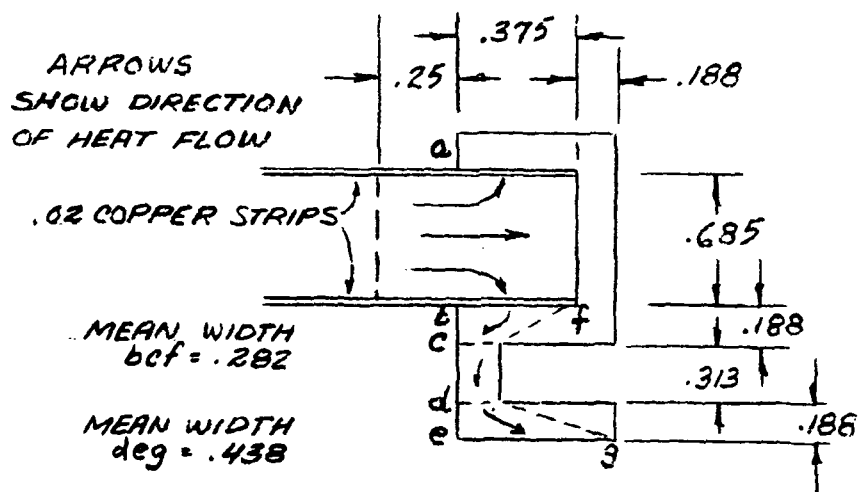


FIGURE 16

ALUMINUM MOUNTING BRACKET #1

(Notes on Table 29, Cont.)

Path DE:

$$X = \left(\frac{2 \frac{3}{4} - 2 \frac{1}{4}}{2} \right) + \frac{2\pi}{4} \left(\frac{1}{4} + \frac{3}{8} \right) = 0.937 \text{ in.}$$

$$K = 1.244 \frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$A = \left(\frac{5}{8} - \frac{1}{4} \right) \left[\frac{5}{8} + 2(0.02) \right] = 0.249 \text{ in.}^2$$

$$\left(\frac{X}{KA} \right)_{DE} = 3.02 \text{ } ^\circ\text{C/watt}$$

Path ABC and DF in Parallel:

$$\left(\frac{X}{KA} \right)_{AC \parallel DE} = \frac{1}{\frac{1}{4.95} + \frac{1}{3.02}} = 1.88 \text{ } ^\circ\text{C/watt}$$

Heat Losses, Q

$$\begin{array}{ll} I^2R \text{ losses to point A (Fig. 15)} & = 2.72 \text{ watts} \\ \text{Core losses to point A (Fig. 15)} & = 2.20 \text{ watts} \\ \text{Total losses to point A (Fig. 15)} & = 4.92 \text{ watts} \end{array}$$

$$\begin{aligned} \text{Remaining core loss} &= \frac{18}{4} - 2.20 \\ &= 2.30 \text{ watts} \end{aligned}$$

$$\text{Remaining Core loss is self-generated} = \frac{2.30}{2} = 1.15 \text{ watts}$$

$$\text{Total loss} = Q = 6.07 \text{ watts}$$

$$\therefore \Delta T = \left(\frac{X}{KA} \right)_{AC \parallel DE} Q = (6.07)(1.88) = 11.41 \text{ } ^\circ\text{C}$$

(Notes on Table 29, Cont.)

Item 10: Core Portion Under Bracket; T From Center of Core to Surface of Core (Fig. 15)

$$x_m = \text{Mean half - width of core} = \frac{1}{2} \left(\frac{5/8}{2} \right) = 0.156 \text{ in.}$$

$$\begin{aligned} A_S &= \text{Top and bottom areas of straight section of core under bracket} \\ &= (2) \left(\frac{7/8}{2} \right) (3/8) = 0.328 \text{ in}^2 \end{aligned}$$

$$\begin{aligned} A_C &= \text{Top and bottom areas of curved section of core under bracket} \\ &= 2 \left[\frac{\pi}{4} (5/8)^2 - (5/8) \left(\frac{1}{4} \right) \right] = 0.301 \text{ in}^2 \end{aligned}$$

$$A_T = \text{Total area} = A_S + A_C = 0.629 \text{ in}^2$$

K = Thermal conductivity of Permalloy 80; heat flow parallel to laminations (See Table 2)

$$= 0.702 \frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{x_m}{KA} \right) = 0.353 \text{ } ^\circ\text{C/ watt}$$

$$\begin{aligned} I^2R \text{ loss} &= 2.72 \text{ watts} \\ \text{Core loss} &= 2.20 + 2.30 = 4.50 \text{ watts} \\ \text{Total loss} &= Q = 7.22 \text{ watts} \end{aligned}$$

$$\Delta T = Q \left(\frac{x_m}{KA} \right) = (7.22)(0.353) = 2.55 \text{ } ^\circ\text{C}$$

Item 11: Interface - Core to Bracket (Interface filled with Sylard 183).

$$X = 0.0 \text{ in.}$$

$$A_S = (\text{Same as } A_S \text{ in item 10}) = 0.328 \text{ in}^2$$

$$A_C = (\text{Same as } A_C \text{ in item 10}) = 0.301 \text{ in}^2$$

$$A_I = \text{Side area of core} = \left(\frac{7/8}{2}\right) [5/8 + 2(0.02)] = 0.291 \text{ in}^2$$

$$A_T = \text{Total area} = A_S + A_C + A_I = (0.328 + 0.301 + 0.291) = 0.920 \text{ in}^2$$

$$K = 0.008 \frac{\text{watts in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA_T}\right) = 1.36 \text{ } ^\circ\text{C/watt}$$

$$Q = (\text{same as } Q \text{ in item 10}) = 7.22 \text{ watts}$$

$$\Delta T = Q \left(\frac{X}{KA_T}\right) = (7.22)(1.36) = 9.82 \text{ } ^\circ\text{C}$$

(Notes on Table 29, Cont.)

Item 12: Bracket to Heat Sink

Heat enters the bracket from the core in the directions indicated by the arrows in Figure 16. The bottom arrow shows a low resistance path from the bottom surface of the core to the heat sink. This path comprises three series sections, bc, cd, and de. The heat conduction parameters for this path are as follows:

Path bc

$$X = 3/16 \text{ in.}$$

$$\text{Mean width of b c f} = \frac{1}{2} (3/8 + 3/16) = 0.282 \text{ in.}$$

$$A_m = \text{Mean width} \times \text{length} = (0.282) \frac{2 \frac{1}{8}}{2} = 0.300 \text{ in}^2$$

$$K = \text{Thermal Conductivity of aluminum} = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA_m} \right)_{bc} = 0.114 \text{ } ^\circ\text{C/watt}$$

Path cd:

$$X = 5/16 \text{ in.}$$

$$A = \text{width} \times \text{length} = (3/16) \times \frac{1}{2} (2 \frac{1}{8}) = 0.200 \text{ in}^2$$

$$K = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA} \right)_{cd} = 0.285 \text{ } ^\circ\text{C/watt}$$

Path de:

$$X = 3/16 \text{ in.}$$

$$\text{Mean width of deg} = \frac{1}{2} \left[3/16 + 3/16 + 3/8 \right] = 0.376 \text{ in.}$$

$$A_m = \text{mean width} \times \text{length} = (0.376) \left(\frac{2 \frac{1}{8}}{2} \right) = 0.400 \text{ in}^2$$

$$K = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA_m} \right)_{de} = 0.085 \text{ } ^\circ\text{C/watt}$$

(Notes on Table 29, Cont.)

Path bc, cd, and de in series:

$$\begin{aligned} \left(\frac{x}{KA} \right)_{be} &= \left(\frac{x}{KA} \right)_{bc} + \left(\frac{x}{KA} \right)_{cd} + \left(\frac{x}{KA} \right)_{de} \\ &= (0.114 + 0.285 + 0.085) = 0.484 \text{ } ^\circ\text{C/watt} \end{aligned}$$

A parallel path of higher thermal resistance is that indicated by the two upper arrows in Figure 16, where heat enters the top and side portions of the bracket and flows through the bottom portion to the heat sink. This path can be divided into three series sections, a-bc, bc-d, and d-e. The heat conduction parameters are as follows:

Path a-bc:

$$x = 3/8 + 3/16 + 0.665 + 3/16 + 3/8 - \frac{1}{2} (3/16) = 1.697 \text{ in.}$$

$$x_m = \text{mean path} = \frac{1.697}{2} = 0.849 \text{ in.}$$

(x_m mean is used because heat is uniformly added)

$$A = (3/16) \times \frac{1}{2} (2 \frac{1}{8}) = 0.200 \text{ in}^2$$

$$K = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{x_m}{KA} \right)_{a-bc} = 0.772 \text{ } ^\circ\text{C/watt}$$

Path bc-d:

$$x = \frac{1}{2} (3/16) + 5/16 = 0.407 \text{ in.}$$

$$A = (3/16) \times \frac{1}{2} (2 \frac{1}{8}) = 0.200 \text{ in}^2$$

$$K = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{x}{KA} \right)_{bc-d} = 0.370 \text{ } ^\circ\text{C/watt}$$

(Notes on Table 29, Cont.)

Path d-e:

$$X = 3/16 \text{ in.}$$

$$\text{Mean width of d e g} = 0.376 \text{ in.}$$

$$A = (0.376) \times \frac{1}{2} (2 \frac{1}{8}) = 0.400 \text{ in}^2$$

$$K = 5.5 \frac{\text{watt in}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA}\right)_{de} = 0.085 \text{ } ^\circ\text{C/watt}$$

Path a-bc, bc-d, and de in series:

$$\begin{aligned}\left(\frac{X}{KA}\right)_{ae} &= \left(\frac{X}{KA}\right)_{a-bc} + \left(\frac{X}{KA}\right)_{bc-d} + \left(\frac{X}{KA}\right)_{d-e} \\ &= (0.772 + 0.370 + 0.085) = 1.227 \text{ } ^\circ\text{C/watt}\end{aligned}$$

Path be and ae in parallel:

$$\left(\frac{X}{KA}\right)_{bellae} = \frac{1}{\frac{1}{0.484} + \frac{1}{1.227}} = 0.347 \text{ } ^\circ\text{C/watt}$$

$$Q = (\text{Same as } Q \text{ in item 11}) = 7.22 \text{ watts}$$

$$\therefore \Delta T = Q \left(\frac{X}{KA}\right)_{bellae} = (7.09)(0.347) = 2.51 \text{ } ^\circ\text{C}$$

The calculated overall temperature rise in Table 29 is 55.3 degrees C based on an assumed winding temperature of 100 degrees C. On adding the T's the primary is found to be 41.7 degrees and the secondaries 54.8 to 55.3 degrees C above the heat sink temperature, and the mean T of the windings is about 49 degrees C. For the calculation to be valid the heat sink temperature would have to be approximately $100 - 49 = 51$ degrees C.

For a heat sink temperature of 85 degrees C addition of the T's shows that the primary is at 126.7 degrees C and the secondaries at 139.8 to 140.3 degrees C, instead of the assumed temperature of 100 degrees C.

Recalculations based on copper losses at assumed winding temperatures of 145 degrees C for the secondaries and 130 degrees C for the primary are presented in Table 30. Under these conditions the overall temperature rise is calculated to be 60.1 degrees C. The primary winding temperature is 129.7 degrees C and the secondaries are 144.4 to 145.1 degrees C.

A detailed thermal analysis of the type described, in addition to yielding information regarding internal temperatures on which choice of materials can be based, also provides valuable data regarding the magnitude of temperature gradients in various areas of the transformer.

The magnitude of these temperature gradients often suggests changes in design that can provide more effective cooling. A study of Table 30 reveals a number of areas for possible improvement.

The large temperature drop between secondary and primary (Item 3) may be reduced by using less insulation in this area. Corona tests confirmed the feasibility of such a change.

Temperature drops at interfaces such as those between the coil tube and the core, and between the core and bracket, may be reduced by minimizing the clearances in these areas and by using a filler of higher thermal conductivity than the filled silicone rubber compound. Examples of high K fillers are Stycast 2850 KT (electrical insulator, $K = .11 \frac{\text{watts}}{\text{in. deg. C}}$ and Eccobond 56C (electrical conductor, silver filled, $K = .22 \frac{\text{watts}}{\text{in. deg. C}}$).

Temperature rise in the core could be reduced by using thicker copper laminations bonded to the core as heat conducting members. The thickness of copper could be increased considerably without increasing unduly the mean length of turn of the winding.

Redesign of the mounting bracket to increase the contact area to the full width of the core would reduce the ΔT between the core and the bracket. A further improvement could be effected by using a solid block of aluminum under the core shunting the losses to the heat sink.

TABLE 30

RECALCULATION OF TEMPERATURE RISE FOR TRANSFORMER OM-2, SUB 6

Heat Conduction Path	χ / KA (°C/watt)	Q (watts)	ΔT (°C)	ΔT Total (°C)	Operating Temp. for 85°C Sink (°C)
1. Sec. 2 to Sec. 1, Layer 2	1.48	0.16	0.24	60.1	145.1
2. Sec. 1, Layer 2 to Sec. 1, Layer 1	0.50	1.66	0.83	59.8	144.8
3. Sec. 1, Layer 1 to Shield	3.51	3.15	11.06	59.0	144.0
4. Shield to Primary	1.03	3.15	3.24	47.9	132.9
5. Primary to Tube	0.38	6.03	2.29	44.7	129.7
6. Tube Wall	1.04	6.03	6.27	42.4	127.4
7. Tube - Core Interface	0.44	6.03	2.65	36.1	121.1
8. Core Portion Under 1/2 Coil	2.17	5.22	5.66	33.5	118.5
9. Core-Coil to Area under Bkt.	1.88	6.37	11.98	27.8	112.8
10. Core Portion under Bracket	0.35	7.69	2.69	15.8	100.8
11. Core-Bracket Interface	1.36	7.69	10.46	13.2	98.2
12. Bracket to Heat Sink	0.35	7.69	2.69	2.7	87.7
13. Heat Sink					85.0

6.3.6 Construction and Fabrication

Elimination of Gaps in the Thermal Path

In the open transformer assembly, voids occur at certain interfaces such as between core and coil and between core and mounting brackets that present large impedances to the flow of heat. To reduce to a minimum the thermal impedances in these areas, the parts are constructed and where necessary machined to achieve as close a fit as possible. Remaining interfaces are filled with a heat conducting material such as a filled silicone rubber compound which is applied in the form of a highly viscous liquid and subsequently cured to an elastomeric solid. A low volatility compound of this type is available in Dow Corning's C6-1102.

Increased thermal conductivity is obtained by the use of silver-filled epoxies in areas where a conducting filler can be tolerated.

Removal of Volatiles

To remove traces of volatiles present in certain of the materials of construction as a result of manufacturing processes, the open transformer after assembly should be baked out for a period of 48 hours in accordance with Process Specification MC-101, given in Table 31.

TABLE 31
PROCESS SPECIFICATION MC-101

Removal Of Volatile Matter From Open Type Space Transformers

1. EQUIPMENT

Forced convection oven, 180 ± 5 degrees C.

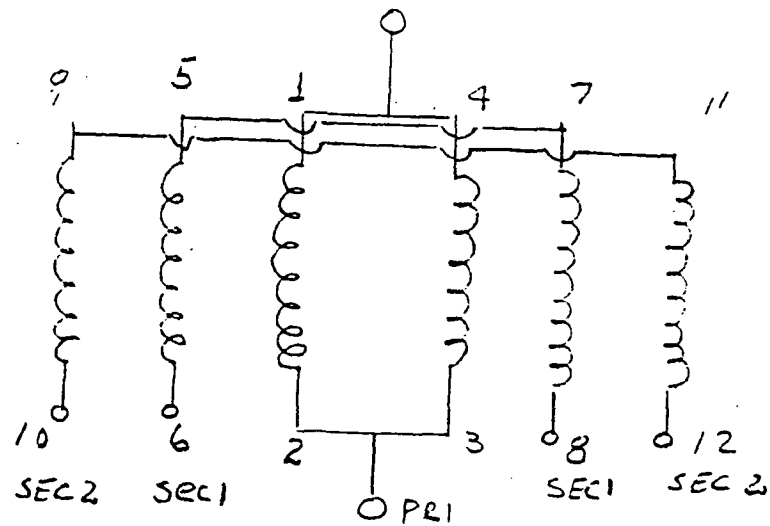
2. PROCEDURE

The transformer after assembly and wiring is placed in the forced convection oven and baked out for a period of 48 hours at a temperature of 180 ± 5 degrees C.

6.3.7 Manufacturing Specification Sheets

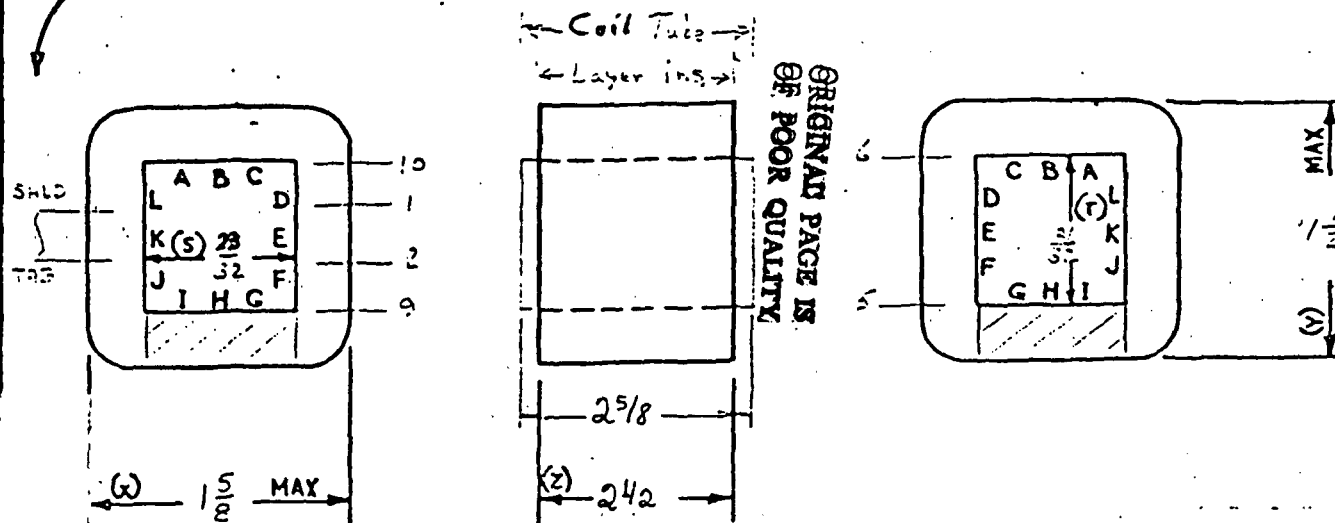
The OM-2 Sub 6 specification sheets which follow, include the schematic, coil layout, and outline drawings.

SCHEMATIC: OM-2 Sub 6



MACHINE ROTATION

COIL A (All dimensions in inches)



TUBE .055 E-30
 TUBE Deluimide Filtraleal
 SHIELD .002 CU X 210
 COILS PER UNIT 1.4518

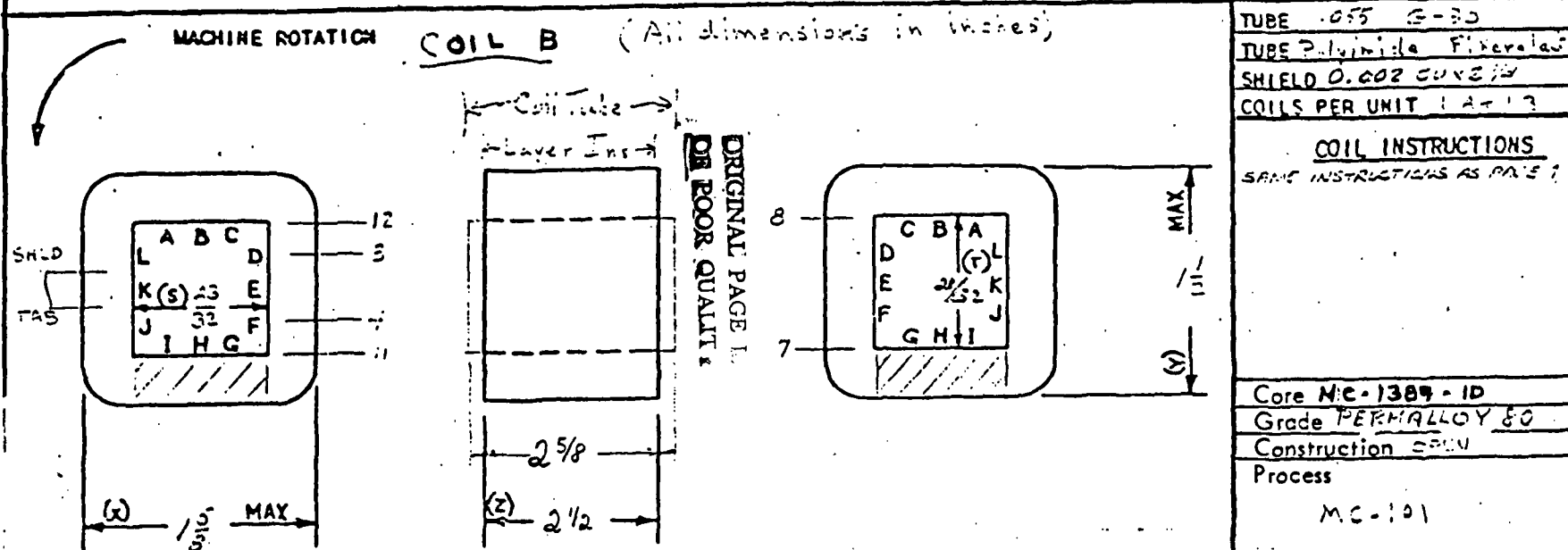
COIL INSTRUCTIONS

- WIND 3X .002 KAPTON OVER TUBE PRIOR TO PRI. WDS.
- WIND OVER START LEAD USING PAD OF 3X .005 KAPTON
- WIND OVER START LEAD USING PAD OF 3X .005 KAPTON

Core MC-1389-10
 Grade PERMALLOY 80
 Construction OPEN
 Process

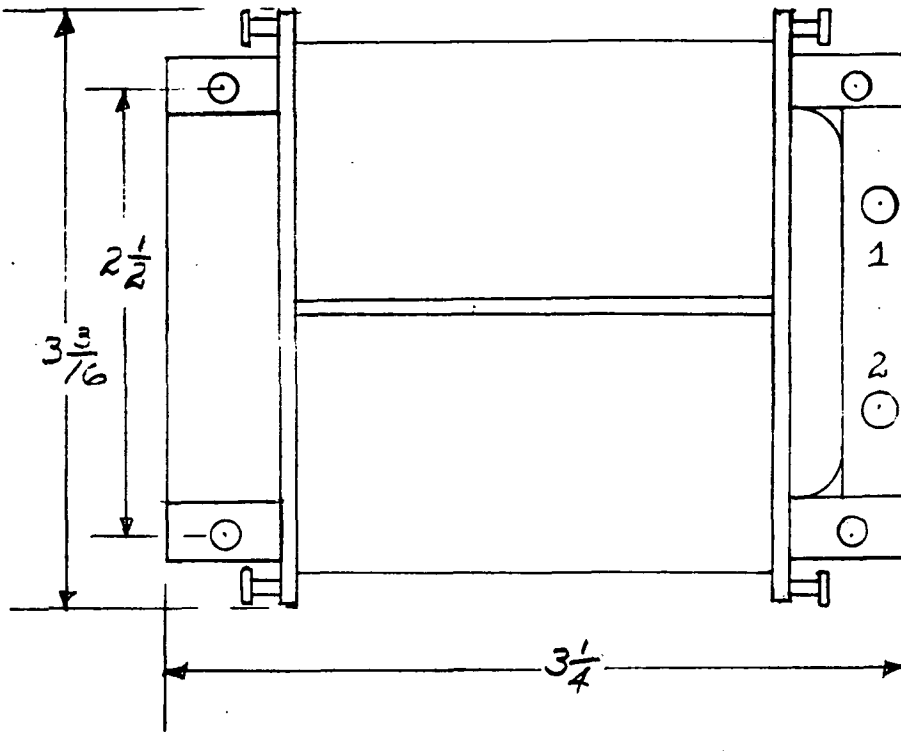
MC-101

WINDING NO.	1-2	5-6	9-10			Input Voltage	200 V
TURNS	41	113	103			Frequency	12 KHz
TURNS AT TAP	---	---	---			Type Of Primary	
WIRE SIZE	#16 HML	#20 HML	#28 HML			No. of Secondaries	2
WINDING WIDTH	2 1/4	2	1 9/16			Voltage Across Each Secondary	#1 1.1 KV #2 1.0 KV
MARGIN	1/2	1/2	15/32			Total Output Voltage	
TURNS/LAYERS	11/1	57/1; 56/1	103/1			Total Output Power	2.62 KVA
LAYER INSUL.	---	5X .002 KAPTON	---			Maximum Mass	1 K9
WIND ON OR OVER	3X .002 KAPT.	SH. WRAP	5-1 WRAP			Bmax	5 KG
LEAD WIRE	SELF	SELF	SELF			Core Loss	18 W
LEAD LENGTH	6"	6"	6"			Efficiency	99.0% @ 20°C
LEAD INSULATION	---	---	---			Weight	964 gm
COIL WRAPPER	4X .005 KAPTON	6X .005 KAPTON	4X .005 KAPTON				
SHIELD WRAPPER	16X .005 KAPTON	---	---				
SHIELD LEAD	CU - TAB	---	---				
D.C. RESISTANCE	0.0452	0.4145	2.712				
WT. OF WIRE	9.090#	0.130#	0.021#				

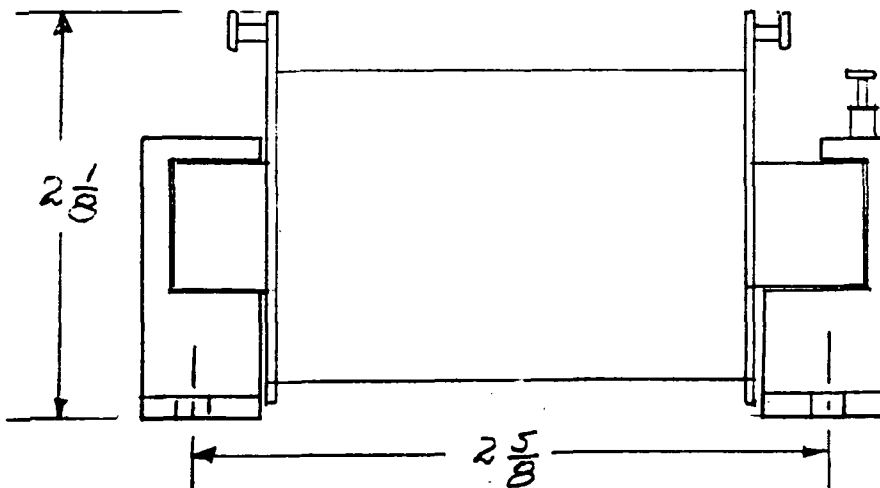


WINDING NO.	3-4	7-5	11-12			Input Voltage	200V
TURNS	41	113	103			Frequency	12 KHZ
TURNS AT TAP	---	---	---			Type Of Primary	
WIRE SIZE	#16 MML	#20 MML	#25 MML			No. of Secondaries	2
WINDING WIDTH	2 1/4	2	1 7/8			Voltage Across Each Secondary	#1 1.1 KV #2 1.0 KV
MARGIN	1/8	1/4	15/32			Total Output Voltage	
TURNS/LAYERS	4L/1	5 1/2; 5 1/2	103/1			Total Output Power	2.62 KVA
LAYER INSUL.	---	5x0.002 KAPTON	---			Maximum Mass	1 KG
WIND ON OR OVER	ON COIL KEPT	SH-WRAP	7-E WRAP			Bmax	5 KG
LEAD WIRE	SELF	SELF	SELF			Core Loss	15 W
LEAD LENGTH	6"	6"	6"			Efficiency	99.0% @ 20°C
LEAD INSULATION	---	---	---			Weight	964 gms.
COIL WRAPPER	4x.005 KAPTON	6x.005 KAPTON	4x.005 KAPTON				
SHIELD WRAPPER	16x.065 KAPTON	---	---				
SHIELD LEAD	CU-TAB	---	---				
D.C. RESISTANCE	0.045Ω	0.414Ω	2.71Ω				
WT. OF WIRE	0.090#	0.130#	0.021#				

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED



ORIGINAL PAGE IS
OF POOR QUALITY



UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES

TOLERANCES: ANGLES $\pm$

FRACTIONS $\pm$

PLACE DECIMALS $\pm$

PLACE DECIMALS $\pm$

PLACE DECIMALS $\pm$

MATERIAL:

CONTR NO.

DR

CHK

A
P
P
D

APPROVED

BY DIRECTION OF



MAGCAP ENGINEERING INC.

222 BOLIVAR STREET CANTON, MASS.

DRAWING TITLE

OM-2 SLR 6 OUTLINE

SIZE

A

CODE IDENT NO.

DRAWING NO.

SCALE

SHEET

6.3.8 Corona Test Results

The OM-2 Sub 6 transformer was built in accordance with Section 6.3.6 and Section 6.3.7. Corona tests were conducted and the test results for this transformer and the OM-2 Sub 7 transformer are given in Table 32. The test results indicate that the OM-2 Sub 6 transformer should be 'corona free' at the required operating voltages.

TABLE 32 CORONA TEST RESULTS ON TRANSFORMERS OM-2, SUB 6 AND SUB 7		
Test Points	OM-2, Sub 6 Permalloy 80 Core CIV/CEV (volts)	OM-2, Sub 7 Ferrite MN-100 Core CIV/CEV (volts)
Secondary 1 to core-shield-primary	3300/3200	4400/4300
Secondary 1 to core-shield	3300/3200	4400/3800
Secondary 1 to primary	4800/4400	5000/4900
Secondary 2 to core-shield primary	4600/4300	4000/3950
Secondary 2 to core-shield	4500/4300	3800/3600
Secondary 2 to primary	4800/4700	4600/4200

6.4 Design Calculations and Test Results for Open Transformer OM-2,

Sub 7

The requirements of the OM-2, Sub 7 transformer are the same as those given in Section 6.3 for the OM-2 Sub 6 transformer. The OM-2 Sub 7 transformer is designed for an operating frequency of 40 kHz with a ferrite core while the OM-2 Sub 6 was designed to operate at 12 kHz with an 80-20 Ni-Fe core. The design procedure used for the OM-2 Sub 7 follows that used in Section 6.3.

6.4.1 Calculation of $A_C A_W$ Product and Selection of Core

The same values for calculating the $A_C A_W$ product of the OM-2 Sub 6 transformer and given in Section 6.3.1 are used in equation (3.5) except that $B_m = 2.25$ kg, $f = 40$ kHz and $(SF)_C = 1$. Thus,

$$A_C A_W = \frac{(2660 + 2420 + 200) (253.4 \times 10^{-5}) \times 10^5}{(4) (2.25) (40000) (0.2)} = 18.6 \text{ cm}^4 = 0.45 \text{ in}^4$$

The core selected was a U-U, MN-100 ferrite core manufactured by Ceramic Magnetics. The D, E, and F dimensions are identical to those for the core used in the OM-2 Sub 6 transformer. The following describes the ferrite core:

Dimensions: D = 5/8 in.; E = 5/8 in.		
F = 7/8 in.; G = 1-5/8 in.		
A_C = Cross-sectional area = DxE		= 0.39 in ²
A_W = Window area	= FxG	= 1.42 in ²
$A_C A_W$		= 0.56 in ⁴
Volume		= 2.93 in ³
Weight		= 0.486 lb.

6.4.2 Calculation of Number of Turns, Wire Size

A two coil construction is used and the physical winding arrangement of each coil is identical. The primary windings on each coil are connected in parallel while both the secondary 1 and secondary 2 windings on each coil are series connected.

Primary

By equation (3.1) the number of primary turns is

$$N_p = \frac{E_p \times 10^5}{4(FF)B_m f A_c (SF)_c} = \frac{200 \times 10^5}{(4)(1)(2.25)(40000)(2.52)(1)} = 22$$

The window width is 1-5/8 in. so for a tube clearance of 1/16 in., the width of the coil tube is 1-9/16 in. The primary winding width is 7/8 in. for 1/16 in. flanges and 9/32 in. margins.

Since the operating frequency is 40 kHz and since this can lead to appreciable skin effect in the wire (see Table 12), the primary is bifilar wound with #20 AWG wire. The primary consists of two layers per coil with 11 turns per layer.

The cross-sectional area of the #20 AWG bare wire is 1020 cir. mils and the primary current is 13.3 A. By equation (3.6) the primary inverse current density is

$$J_p = \frac{a_p}{I_p} = \frac{2(1020)}{(13.3/2)A} \text{ cir. mils} = 307 \text{ cir. mils/A}$$

Secondary 1

Using equation (3.1) the number of secondary 1 turns is

$$N_{S1} = \frac{V_{S1}}{V_p} N_p = \left(\frac{1100}{200}\right) \times 22 = 121$$

For 7/32 in. margins we have

$$\text{Sec. 1 winding width} = 1 \frac{9}{16} - 2 \left(\frac{1}{16} + \frac{7}{32} \right) = 1 \text{ in.}$$

Secondary 1 is bifilar wound with #23 AWG wire which has a bare cross-sectional area of 511 cir. mils. Each coil consists of three layers with 20 turns per layers. An extra turn is placed on one coil to give a total of 121 turns by connecting the two coils in series. The secondary 1 current is 2.2 A so the inverse current density is

$$J_{S2} = \frac{2(511)}{2.2A} \text{ cir mils} = 464 \text{ cir mils/A}$$

Secondary 2

The number of secondary two turns by equation (3.1) is

$$N_{S2} = \left(\frac{V_{S2}}{V_p} \right) N_p = \left(\frac{1000}{200} \right) \times 22 = 110$$

The secondary 2 winding width is 7/8 in. for 9/32 margins. A single layer of #28 AWG coils are series connected. The #28 AWG bare wire cross-sectional area is 159 cir. mils, the secondary 2 current is 0.2 A so the inverse current density is

$$J_{S2} = \frac{159 \text{ cir mils}}{0.2 A} = 795 \text{ cir mils/A}$$

6.4.3 Layer and Interwinding Insulation, Coil Build, Window Space Factor

Kapton film of 0.002 in. thickness is used for the layer insulation while Kapton film of 0.005 in. thickness is used for the interwinding insulation. The coil buildup is given in Table 33.

TABLE 33

COIL BUILD-UP FOR EACH COIL OF TRANSFORMER OM-2 SUB 7

Build-up Sequence	Incremental Build (in.)	Total Build (in.)
Tube Wall	0.055	0.055
Tube Wrapper (3x0.002 in.)	0.006	0.061
Primary, Layer 1, 2x #20 HML	0.035	0.096
Primary, Layer 1 Wrapper (4x0.002 in.)	0.008	0.104
Primary, Layer 2, 2x #20 HML	0.035	0.139
Primary, Layer 2 Wrapper (6x0.005 in.)	0.030	0.169
Sec. 1, Layer 1, 2x #23 HML	0.025	0.194
Sec. 1, Layer 1 Wrapper (2x0.002 in.)	0.004	0.198
Sec. 1, Layer 2, 2x #23 HML	0.025	0.223
Sec. 1, Layer 2 Wrapper (2x0.002 in.)	0.004	0.227
Sec. 1, Layer 3, 2x #23 HML	0.025	0.252
Sec. 1, Layer 3 Wrapper (6x0.005 in.)	0.030	0.282
Sec. 2, #28 HML	0.015	0.297
Sec. 2 Wrapper (4x0.005 in.)	0.020	0.317

A window space factor, $(SF)_W$, of 20 percent was assumed in calculating the $A_C A_W$ product in Section 6.4.1. For this design the actual window space factor is

$$(SF)_W = \frac{4N_p a_p + 2N_{S1} a_{S1} + N_{S2} a_{S2}}{A_W}$$

$$(SF)_W = \frac{(4)(22)(804 \times 10^{-6} \text{ in}^2) + (2)(121)(401 \times 10^{-6} \text{ in}^2) + (110)(125 \times 10^{-6} \text{ in}^2)}{(1.42 \text{ in}^2)}$$

$$(SF)_W = 0.13$$

6.4.4 Calculation of Losses and Efficiency

Core Loss

From the vendor's data, the specific core loss is 15.8 watts per pound for a MN-100 ferrite, U-U type core under sinusoidal voltage excitation at 40 kHz and 5 KG. The sinusoidal excitation value of the specific core loss is used since no data exists for the same conditions under square wave excitation. The weight of the core is 0.486 lb. so the core loss at 20°C is 7.7 watts.

Conductor (I^2R) Loss

Equations (3.7) through (3.11) and the information given in Table 32 are used to calculate the I^2R loss for each winding. The results are given in Table 34. The inside dimensions of the coil tube are 21/32 in. x 23/32 in.

TABLE 34

CONDUCTOR (I^2R) LOSSES FOR TRANSFORMER OM-2, SUB 7

	Primary	Secondary 1	Secondary 2
Average Number of Turns/Coil	22	60.5	55
MLT/Coil (in.)	3.38	4.07	4.57
Winding Length/Coil (ft)	6.20	20.69	20.95
Wire Size (AWG)	2x#20	2x#23	#28
DC Resistance (ohms) per ft	0.101	0.203	0.0653
DC Resistance @ 20°C (ohms)	0.0157 ⁽¹⁾	0.420 ⁽²⁾	2.74 ⁽²⁾
Current (A)	13.3	2.2	0.2
I^2R Loss @ 20°C (watts)	2.78	2.03	0.11
Total I^2R Loss @ 20°C = 2.78 + 2.03 + 0.11 = 4.9 watts			
(1) Two coils in parallel (2) Two coils in series			

Efficiency

The computed efficiency using equation (3.12) is

$$\eta = \left(\frac{P_{OUT}}{P_{OUT} + P_T} \right) \times 100 = \frac{2620 \times 100}{2620 + 7.7 + 4.9} = 99.5\% @ 20^\circ\text{C}$$

6.4.5 Calculation of Temperature Rise

The temperature rise of this transformer is calculated in the same manner as the OM-2 Sub 6 transformer temperature rise in Section 6.3.5. Again, two copper laminations, 0.02 in. thick, are bonded to opposite surfaces of the ferrite core to aid in the conduction of heat to the mounting brackets.

As in Section 6.3.5, it is assumed in the first approximation of the temperature rise, that all the windings are at 100° C. The I²R loss of each winding is then computed for this temperature. In addition, it is assumed that the core loss increases by a factor of 2 from 20° C to 100° C.

The pertinent coil dimensions for the heat conduction process are listed in Table 35. The first approximation of the temperature rise is given in Table 36. The notes following Table 36 give detailed calculations for items 8 through 13.

Adding the ΔT 's in Table 36, it is seen that the temperature rise of primary and secondary windings is from 38.2 to 46.5 degrees. At a heat sink temperature of 85 degrees, the temperature of the windings is between 123.2 and 131.5 degrees.

Since the assumed winding temperature was 100 degrees in the calculations, a recalculation is made taking into consideration the increased copper losses at the higher winding temperature.

Table 37 shows the results of such a recalculation using an assumed winding temperature of 128° C for the primary and 135°C for the secondaries. The core temperature is assumed to remain at 100° C.

TABLE 35

DIMENSIONAL DATA FOR EACH COIL OF TRANSFORMER OM-2 SUB7

Material	Thickness (in.)	Heat Path Σ , (in.)	Total Build (in.)	Mean Length of Insulation (in.)	Winding Width (in.)	Mean Surface Area (in ²)
Tube Wall	0.055	0.055	0.055	2.92	7/8	2.56
Tube Wrapper (3x0.002 in.)	0.006	0.00755	0.061	3.12	7/8	2.73
Pri: Layer 1 Wire Insulation	0.00155		0.063			
Layer 1 Bare Wire Dia.	0.0320		0.095			
Layer 1 Wire Insulation	0.00155	0.0111	0.096	3.38	7/8	2.96
Layer 1 Wrapper (4x0.002 in.)	0.008		0.104			
Layer 2 Wire Insulation	0.00155		0.106			
Layer 2 Bare Wire Dia.	0.0320	0.0329	0.138	3.72	15/16	3.49
Layer 2 Wire Insulation	0.00155		0.139			
Layer 2 Wrapper (6x0.005 in.)	0.030		0.169			
Sec 1: Layer 1 Wire Insulation	0.00155	0.0067	0.171	3.98	1	3.98
Layer 1 Bare Wire Dia.	0.0226		0.193			
Layer 1 Wire Insulation	0.00135		0.195			
Layer 1 Wrapper (2x0.002 in.)	0.004	0.0067	0.199	3.98	1	3.98
Layer 2 Wire Insulation	0.00135		0.200			
Layer 2 Bare Wire Dia.	0.0226		0.222			

TABLE 35 CONCLUDED

Material	Thickness (in.)	Heat Path χ , (in.)	Total Build (in.)	Mean Length of Insulation (in.)	Winding Width (in.)	Mean Surface Area (in ²)
Layer 2 Wire Insulation	0.00135	0.0067	0.224	4.17	1	4.17
Layer 2 Wrapper (2x0.002 in.)	0.004		0.228			
Layer 3 Wire Insulation	0.00135		0.229			
Layer 3 Bare Wire Dia.	0.0226	0.0324	0.252	4.43	15/16	4.15
Layer 3 Wire Insulation	0.00135		0.253			
Layer 3 Wrapper (6x0.005 in.)	0.030		0.283			
Sec 2: Wire Insulation	0.00105		0.284			

TABLE 36

CALCULATION OF TEMPERATURE RISE FOR TRANSFORMER OM-2 SUB7

Heat Conduction Path	χ (in.)	K ($\frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$)	A (in ²)	χ/KA ($^\circ\text{C/watt}$)	Q @ 100 $^\circ\text{C}$ (watts)	ΔT ($^\circ\text{C}$)	ΔT Total ($^\circ\text{C}$)
1. Sec. 2 to Sec. 1, Layer 3 Add Losses of Sec. 1, Layer 3	0.0324	0.003	4.15	2.60	0.072 0.44	0.19	46.5
2. Sec. 1, Layer 3 to Sec. 1, Layer 2 Add Losses of Sec. 1, Layer 2	0.0067	0.003	4.17	0.54	0.52 0.44	0.28	46.3
3. Sec. 1, Layer 2 to Sec. 1, Layer 1 Add Losses of Sec. 1, Layer 1	0.0067	0.003	3.98	0.56	0.96 0.44	0.54	46.0
4. Sec. 1, Layer 1 to Pri., Layer 2 Add Losses of Pri., Layer 2	0.0329	0.003	3.49	3.14	1.40 0.91	4.40	45.5
5. Pri., Layer 2 to Pri. Layer 1 Add Losses of Pri., Layer 1	0.0111	0.003	2.96	1.24	2.31 0.91	2.86	41.1
6. Pri. Layer 1 to Tube	0.00755	0.003	2.73	0.92	3.22	2.96	38.2
7. Tube Wall	0.055	0.008	2.56	2.69	3.22	8.66	35.3
8. Tube to Core Interface	0.021	0.008	2.33	1.13	3.22	3.53	26.6
9. Core Portion Under 1/2 of Coil	0.438	0.732	0.42	1.42	2.51	1.78	23.1
10. Core-Coil to Area Under Bracket	0.866	0.732	0.42	2.82	3.98	11.22	21.3
11. Core Interior Under Bracket	0.239	0.159	1.64	0.92	5.45	5.01	10.1
12. Core to Bracket Interface	0.01	0.008	1.64	0.76	5.45	4.15	5.1
13. Bracket to Heat Sink		5.5		0.17	5.45	0.93	0.9

NOTES ON TABLE 36

Item 8: Tube to Core Interface (Interface Filled with Sylgard 183)

$$X = 0.021 \text{ in. (see item 7 of Notes on Table 29)}$$

$$K = 0.008 \text{ watt in./in.}^2 \text{ } ^\circ\text{C}$$

$$\text{Mean Length of Ins.} = \frac{2(21/32 + 23/32) + 2(5/8 + 0.665)}{2} = 2.665 \text{ in.}$$

$$\text{Winding Width} = 7/8 \text{ in.}$$

$$\text{Area} = A = (2.665)(7/8) = 2.33 \text{ in}^2$$

$$\frac{X}{KA} = \frac{0.021}{(0.008)(2.33)} = 1.13 \text{ } ^\circ\text{C/watt}$$

$$Q @ 100^\circ \text{ C (Coil Loss)} = 3.22 \text{ watts}$$

$$\Delta T = \left(\frac{X}{KA}\right)Q = (1.13)(3.22) = 3.64^\circ \text{ C}$$

Item 9: Core Portion Under 1/2 of Coil

$$X = 1/2 \text{ pri. winding width} = 1/2 (7/8) = 7/16 \text{ in.}$$

$$K = \text{Thermal conductivity of } 5/8 \text{ in. thick MN-100 ferrite core} \\ \text{with two 0.02 in. copper laminations; heat flow parallel to} \\ \text{laminations (see Table 2)} = 0.732 \left(\frac{\text{watts in.}}{\text{in}^2 \text{ } ^\circ\text{C}} \right)$$

$$A = \text{Cross-sectional area of core and copper laminations} = \\ (5/8)(0.665) = 0.42 \text{ in}^2$$

$$\frac{X}{KA} = 1.42^\circ \text{ C/watt}$$

MMPL = Mean Magnetic Path Length

$$\text{MMPL} = \frac{2(G+F) + 2[(G+2E) + (F+2E)]}{2} = 2(G+F) + 4E$$

$$G = 1 \frac{5}{8} \text{ in.}; F = 7/8; E = 5/8''$$

$$\text{MMPL} = 2 \left(1 \frac{5}{8} + 7/8 \right) + 4(5/8) = 7.50 \text{ in.}$$

NOTES ON TABLE 36 CONTINUED

Core Losses for 7/16 in. of core under winding @ 100° C =

$$\left(\frac{7/16 \text{ in}}{7.50 \text{ in}}\right) (2 \times 7.7 \text{ watts}) = 0.90 \text{ watts}$$

$$1/2 \text{ Coil } I^2R \text{ loss @ } 100^\circ\text{C} = \left(\frac{3.22}{2}\right) = 1.61 \text{ watts}$$

$$Q = I^2R \text{ Loss} + \text{Core Loss} = 1.61 + 0.90 = 2.51 \text{ watts}$$

I^2R loss is uniformly added and core loss is self-generated so

$$\Delta T = \left(\frac{\chi}{KA}\right) \left(\frac{Q}{2}\right) = (1.42) \left(\frac{2.51}{2}\right) = 1.78^\circ \text{ C}$$

Item 10: Core-End of Coil to Area Under Bracket (fig. 17)

$$\chi = 3/8 + \frac{2\pi}{4} (5/16) = 0.866 \text{ in.}$$

$$K = 0.732 \text{ watt in.}/\text{in.}^2 \text{ } ^\circ\text{C}$$

$$A = (5/8) (0.665) = 0.42 \text{ in.}^2$$

$$\frac{\chi}{KA} = 2.82 \text{ } ^\circ\text{C}/\text{watt}$$

$$\text{Remaining core loss} = 1/4 (15.4) - 0.9 = 2.95 \text{ watts}$$

$$\text{Remaining core loss is self-generated} = 2.95/2 = 1.47 \text{ watts}$$

$$\text{Loss from Item 9 above} = 2.51 \text{ watts}$$

$$Q = 1.47 + 2.51 = 3.98 \text{ watts}$$

$$\Delta T = \left(\frac{\chi}{KA}\right) Q = (2.82) (3.98) = 11.22^\circ\text{C}$$

Item 11: Core Portion Under Bracket; T from Center of Core to Surface of Core (fig. 18)

The mean heat path distance, χ_m , is determined as follows.

Nine heat paths, G_1 , through C_9 , at equal angles of 22.5° , are drawn to the outside surfaces as shown. Since ΔT is to be computed from the center of the core, χ_m is

(Notes on Table 36, Cont.)

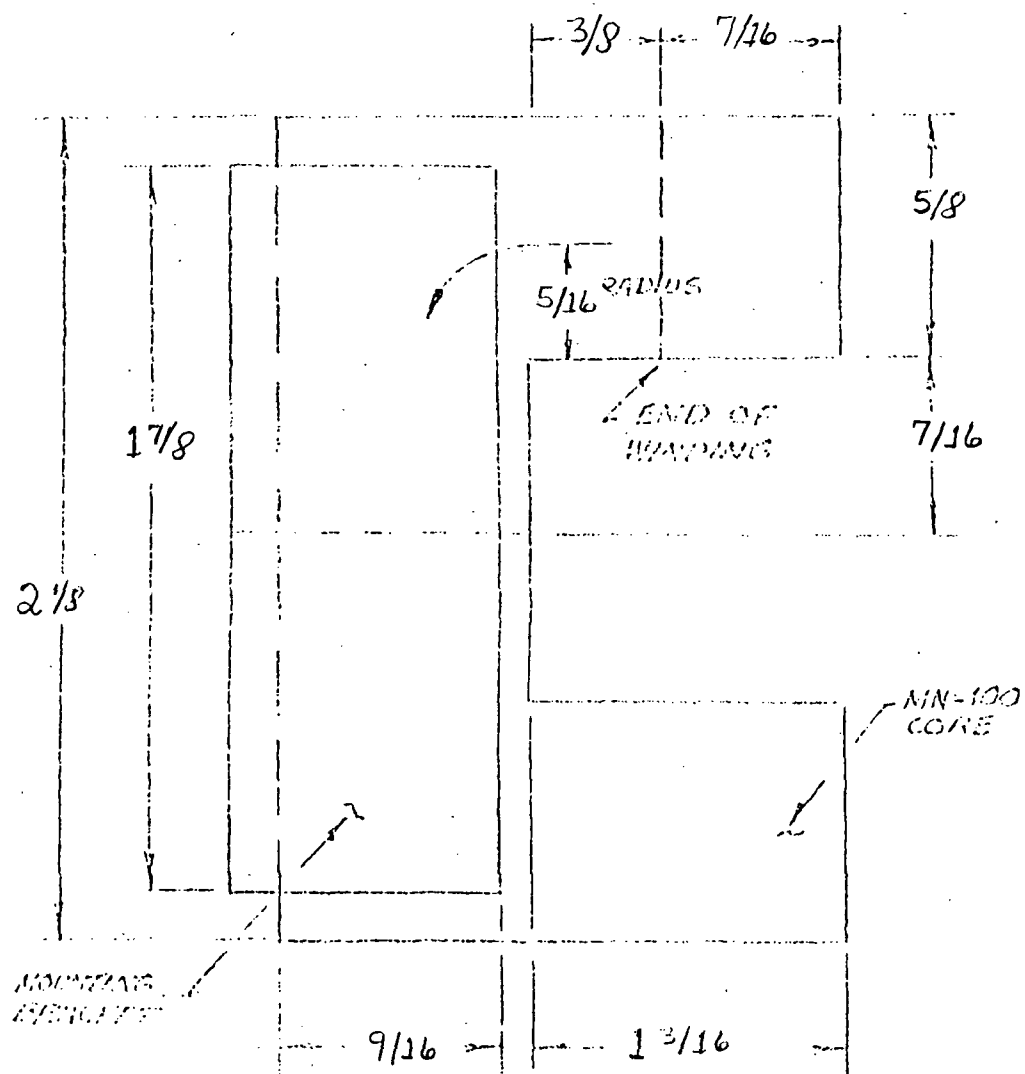


FIGURE 17

FERRITE CORE AND MOUNTING BRACKET

(TOP VIEW - DIMENSIONS IN INCHES)

(Notes on Table 36, Cont.)

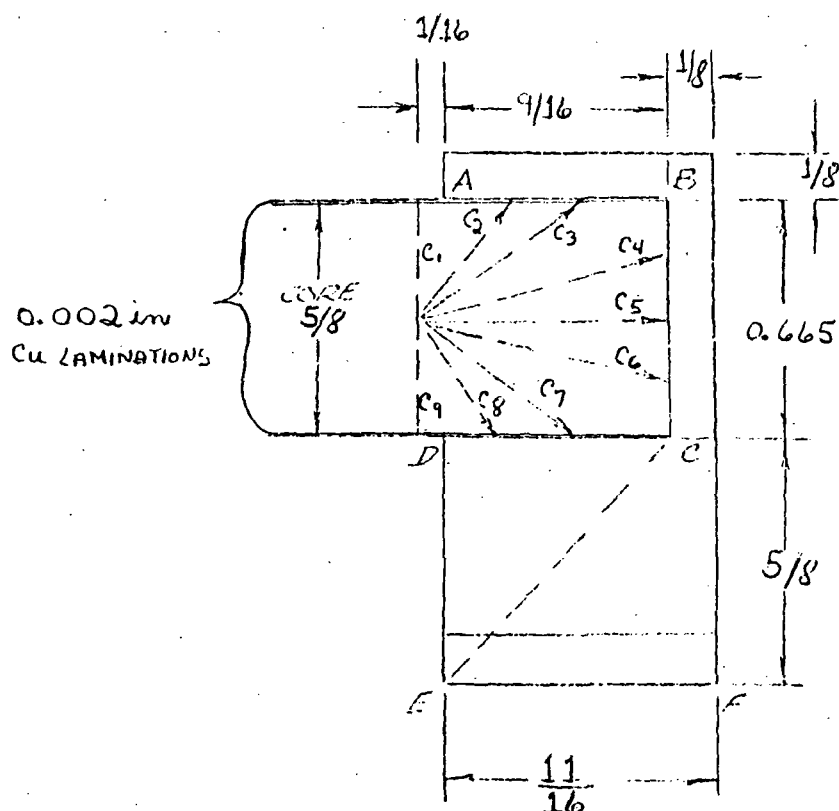


FIGURE 18

FERRITE CORE AND MOUNTING BRACKET #2

(END VIEW - DIMENSIONS IN INCHES)

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(Notes on Table 36, Cont.)

one-half of the average of the nine heat paths.

$$c_1 = c_9 = \frac{0.665}{2} = 0.333 \text{ in.}$$

$$c_2 = c_8 = \sqrt{c_1^2 + c_1^2 \tan^2 \theta} = \frac{c_1}{\cos 2\theta} = \frac{0.333}{\cos 22.5^\circ} = 0.360 \text{ in.}$$

$$c_3 = c_7 = \sqrt{c_1^2 + c_1^2 \tan^2 2\theta} = \frac{c_1}{\cos 2\theta} = \frac{0.333}{\cos 45^\circ} = 0.470 \text{ in.}$$

$$c_5 = 5/8 = 0.625 \text{ in.}$$

$$c_4 = c_6 = \sqrt{c_5^2 + c_5^2 \tan^2 \theta} = \frac{c_5}{\cos \theta} = \frac{0.625}{\cos 22.5^\circ} = 0.676$$

$$X_{\text{avg}} = \frac{1}{9} \sum_{i=1}^9 c_i = \frac{4.303}{9} = 0.478 \text{ in.}$$

$$X_m = \frac{0.478}{2} = 0.239 \text{ in.}$$

K = Thermal Conductivity of MN-100 ferrite material (see Table 2) = 0.159 watt in./in.² °C.

$$A = \underbrace{\left(\frac{1\frac{7}{8}}{2}\right)(9/16)}_{\text{Top Area}} + \underbrace{\left(\frac{1\frac{7}{8}}{2}\right)(9/16)}_{\text{Bottom Area}} + \underbrace{\left(\frac{1\frac{7}{8}}{2}\right)(5/8)}_{\text{Side Area}} = 1.64 \text{ in.}^2$$

$$\left(\frac{X_m}{KA}\right) = 0.92 \text{ °C/watt}$$

$$Q = I^2 R \text{ Loss} + \text{Core Loss} = 1.61 + 15.4/4 = 5.45 \text{ watts}$$

$$\Delta T = \left(\frac{X_m}{KA}\right) Q = (0.92)(5.45) = 5.01^\circ\text{C}$$

(Notes on Table 36, Cont.)

Item 12: Interface - Core to Bracket (Interface filled with Sylgard 183)

$$X = 0.01 \text{ in.}$$

$$A = 1.64 \text{ in}^2 \text{ (same as } A \text{ in Item 11)}$$

$$K = 0.008 \text{ watt in.in.}^2 \text{ } ^\circ\text{C}$$

$$\left(\frac{X}{KA}\right) = 0.76 \text{ } ^\circ\text{C/watt}$$

$$Q = 5.45 \text{ watts (same as } Q \text{ in Item 11)}$$

$$\Delta T = \left(\frac{X}{KA}\right)Q = (0.76)(5.45) = 4.15^\circ \text{ C}$$

Item 13: Bracket to Heat Sink

There are two heat paths which are considered to be in parallel; path DC-EF, and path A-B-C in series with C-EF (see fig. 18)

Path DC-EF

$$X = 5/8 \text{ in.}$$

$$A = \frac{(9/16 + 11/16)}{2} \left(\frac{1^{7/8}}{2}\right) = 0.586 \text{ in.}^2$$

$$K = \text{Thermal Conductivity of Aluminum} = \frac{5.5 \text{ watt in.}}{\text{in}^2 \text{ } ^\circ\text{C}}$$

$$\left(\frac{X}{KA}\right)_{DF} = 0.194 \text{ } ^\circ\text{C/watt}$$

Path A-F Parallel with Path DC-EF

$$\left(\frac{X}{KA}\right)_{AF||DF} = \frac{1}{\frac{1}{0.194} + \frac{1}{1.35}} = \frac{1}{5.895} = 0.17 \text{ } ^\circ\text{C/watt}$$

$$Q @ 100^\circ \text{ C} = 5.45 \text{ watts}$$

$$\Delta T = \left(\frac{X}{KA}\right)Q = (0.17)(5.45) = 0.93 \text{ } ^\circ\text{C}$$

TABLE 37

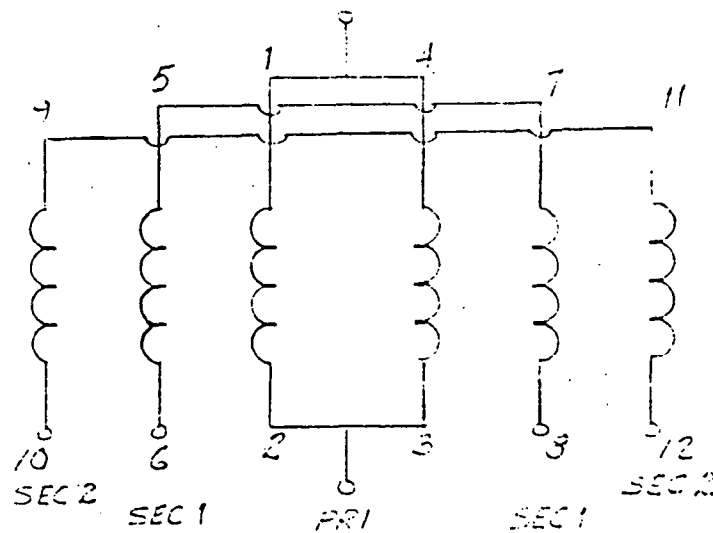
RECALCULATION OF TEMPERATURE RISE FOR TRANSFORMER OM-2, SUB 7

Heat Conduction Path	Σ /KA (°C/watt)	Q (watts)	ΔT (°C)	ΔT Total (°C)	Operating Temp. for 85°C Sink (°C)
1. Sec. 2 to Sec. 1, Layer 3	2.60	0.080	0.21	49.8	134.8
2. Sec. 1, Layer 3 to Sec. 1, Layer 2	0.54	0.57	0.31	49.6	134.5
3. Sec. 1, Layer 2 to Sec. 1, Layer 1	0.56	1.06	0.59	49.3	134.3
4. Sec. 1, Layer 1 to Pri., Layer 2	3.14	1.55	4.87	48.7	133.7
5. Pri. Layer 2 to Pri., Layer 1	1.24	2.54	3.15	43.8	128.8
6. Pri., Layer 1 to Tube Wall	0.92	3.53	3.25	40.7	125.7
7. Tube Wall	2.69	3.53	9.50	37.4	122.4
8. Tube-Core Interface	1.13	3.53	3.99	27.9	112.9
9. Core Portion under 1/2 Coil	1.42	2.67	1.90	23.9	108.9
10. Core-Coil to Area Under Bracket	2.82	4.14	11.67	22.0	107.0
11. Core Interior under Bracket	0.92	5.61	5.16	10.4	95.4
12. Core Bracket Interface	0.76	5.61	4.26	5.2	90.2
13. Bracket to Heat Sink	0.17	5.61	0.95	1.0	86.0
14. Heat Sink					85.0

6.4.6 Manufacturing Specification Sheets

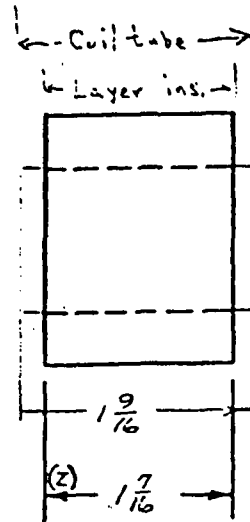
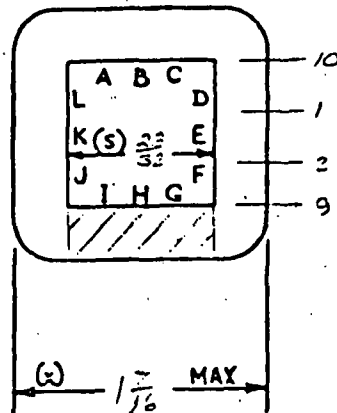
The electrical schematic, coil layout and outline drawings for transformer OM-2 Sub 7 are as follows:

SCHEMATIC OM-2, Sub 7

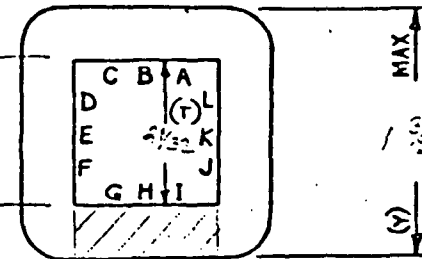


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MACHINE ROTATION

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(All Dimensions in Inches)



Two coils per unit

TUBE .055 G-30

TUBE .055 G-30

SHIELD None

COILS PER UNIT 2

COIL INSTRUCTIONS

- * Bifilar windings
- * 3 x .002 in. KAPTON
- * wound over tube
- * SS - Single spacer

Core U-U

Grade MN-100

Construction Open

Process

MC-101

WINDING NO.	1-2; 3-4	5-6; 7-8	9-10; 11-12			Input Voltage	200V
TURNS	22; 22	61; 60	55; 55			Frequency	20 KHz
TURNS AT TAP	---	---	---			Type Of Primary	
WIRE SIZE	2x #20 HML*	2x #20 HML*	#20 HML			No. of Secondaries	2
WINDING WIDTH	7/8	1	7/8			Voltage Across Each Secondary	#1 1.1 KV #2 1.0 KV
MARGIN	9/32	9/32	9/32			Total Output Voltage	
TURNS / LAYERS	11/2	25/3	55/1			Total Output Power	2.62 KW
LAYER INSUL.	2x .002 KAPTON	2x .002 KAPTON	---			Maximum Mass	1 K9
WIND ON OR OVER	TUBE	1-2 WRAP	5-6 WRAP			Bmax	2.25 KG
LEAD WIRE	SELF	SELF	SELF			Core Loss	7.7 W
LEAD LENGTH	6"	6"	6"			Efficiency	99.5 % @ 20°C
LEAD INSULATION	SS ***	SS ***	SS ***			Weight	795 gm
COIL WRAPPER	3x .005 KAPTON	6x .005 KAPTON	1x .005 KAPTON				
SHIELD WRAPPER	---	---	---				
SHIELD LEAD	---	---	---				
D.C. RESISTANCE	0.031Ω	0.210Ω	1.37Ω				
WT. OF WIRE	0.39#	0.06#	0.010#				

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		CONTR NO. <i>NAS3-17781</i>				MAGCAP ENGINEERING INC. 222 BOLIVAR STREET CANTON, MASS.	
TOLERANCES: ANGLES $\pm$ -- FRACTIONS $\pm \frac{1}{64}$ 3 PLACE DECIMALS $\pm$ -- 2 PLACE DECIMALS $\pm$ -- 1 PLACE DECIMALS $\pm$ --		DR <i>RFC</i> 12/16/60 CHK A P P D		DRAWING TITLE <i>OM-2 SUB 7 OUTLINE</i>			
MATERIAL:		APPROVED		SIZE A		CODE IDENT NO.	
		BY DIRECTION OF		DRAWING NO.			
		SCALE <i>FULL</i>				SHEET	

6.4.7 Corona Test Results

The OM-2 Sub 7 transformer was built in accordance with Section 6.4.6 and Section 6.3.6. The results of the Corona tests conducted on this transformer are given in Table 32. The test results indicate that this transformer should be 'corona free' at the required operating voltages.

6.5 Comparison of Open Transformers OM-2 Sub 6 and OM-2 Sub 7

In Table 38 a comparison is made between some of the characteristics of the OM-2 Sub 6 and OM-2 Sub 7 transformer. The electrical requirements are the same for both of these transformers.

TABLE 38

COMPARISON OF TRANSFORMERS OM-2 SUB 6 AND OM-2 SUB 7

Design Number	OM-2, Sub 6	OM-2, Sub 7
Core Material	Permalloy 80	Ferrite MN-100
Weight of core	1 lb	0.486 lb
Frequency	12 kHz	40 kHz
Maximum Flux Density	5 KG	2.25 KG
Core loss (20° C)	18 watts	7.7 watts
I^2R loss (20° C)	8.3 watts	4.9 watts
Total loss (20° C)	26.3 watts	12.6 watts
Efficiency (20° C)	99.0 %	99.5%
Temperature rise	60° C	50° C
Weight	964 gm (2.13 lb)	795 gm (1.75 lb)

A comparison of these two transformers shows that the OM-2 Sub 7 transformer is somewhat better than the OM-2 Sub 6 with respect to weight, losses, efficiency, and temperature rise. However, this conclusion is subject to modification when the following physical difference of the two transformers is taken into consideration. The OM-2 Sub 6 transformer is designed with an electrostatic shield between the primary and secondary 1 windings while the OM-2 Sub 7 is not. Because of the shield the OM-2 Sub 6 uses approximately 0.07 inches more of primary to secondary 1 layer insulation. From Table 30 it is seen that the temperature rise is approximately 11°C due to the shield insulation. If the shield and shield insulation were removed in the OM-2 Sub 6, then both transformers would have approximately the same temperature rise. A decrease in the I^2R loss of the secondaries would also result since the mean-length of turn would decrease. However, no significant decrease in weight would occur.

In addition, it should be noted that possible improvements could be made in the OM-2 Sub 6 transformer if it were designed for 40 kHz rather than 12 kHz. The advantage of designing with high frequency and low flux density to yield lower possible transformer losses and weight is discussed in Section 4.2. However, increasing the OM-2 Sub 6 frequency to 40 kHz would require a complete re-design in order to make valid comparisons with the 40 kHz OM-2 Sub 7 transformer.

6.6 Other Open Transformer Designs

Preliminary design work was done on the OM-10, OS-10, and OS-15 transformers. This work indicated that encapsulation would be required to fulfill the corona free specification. Thus, no finalized designs of

of these transformers were completed and, hence, none of these transformers were built.

7.0 THE ENCAPSULATED TRANSFORMER

As was stated in Section 4.1, experimental evidence exists indicating that the open-to-space approach is feasible up to voltage levels of 3 KV. While the upper voltage limit of the open transformer has not been established under the present contract, the data on corona indicate that for voltages of 10 or 15 KV, representing two of the contract designs, spacings and insulation thicknesses would become excessively large using the open-to-space approach. For voltages of this magnitude encapsulation of the windings or of the entire transformer is required to permit operation in air at sea level. Impregnation-encapsulation improves the cooling of the transformer by filling voids in the assembly with heat-conducting material, and therefore may be advantageous also in low-voltage units in which cooling may present a problem.

7.1 Materials for Encapsulated Transformers

7.1.1 Layer And Interwinding Insulation

The layer insulation system should include a material of open structure capable of ready penetration by the resinous impregnant-encapsulant. This requirement is met by non-woven webs composed of polyester or aramid fibers having a preferred direction of orientation. Satisfactory results in the program were obtained with layer insulation consisting of alternate plies of polyimide film (Kapton H), 2 or 5 mils, and an oriented polyester web (Pellon Corp. No. 7200), 1.2 mils, wound with the direction of orientation transverse to the turns of wire. The wire is wound directly over the Kapton layer to minimize compression of the web. The polyester web was chosen in preference to aramid (Pellon Corp. No. 2109 and 2104) because of its availability in thinner gauges.

7.1.2 Impregnating And Encapsulating Resins

The selection of suitable impregnating resins requires an understanding of the physical mechanisms involved in the impregnation of windings. Investigations performed during the experimental program (Section 5.4) pointed to the following probable causes of low corona inception voltages of impregnated specimen coils:

- 1) Incomplete penetration of the resin into the windings.
- 2) Shrinkage of the resin during cure.
- 3) Shrinkage of the cured resin upon cooling from the cure temperature to room temperature.
- 4) Cracking of the resin due to thermal stresses.

Any of the above mechanisms can cause voids to be formed within the winding. The voltage gradient across these voids can be high relative to the voltage gradient across the insulation in which the void occurs. Thus, these voids would lead to low corona inception voltage. Additionally, since the coils are impregnated under vacuum, the voids may be filled with air at less than atmospheric pressure after solidification of the resin. As a result, a poorly impregnated coil can exhibit a corona inception voltage lower than that of the unimpregnated coil.

Elimination of the causes of low corona inception voltages requires first, the selection of a suitable resin, and second, the establishment of an impregnating process designed to minimize the factors that lead to low CIV.

The properties of a suitable resin include the following:

- 1) Low viscosity
- 2) Long pot life
- 3) Low shrinkage on cure
- 4) Low coefficient of thermal expansion
- 5) Low temperature cure
- 6) Low peak exotherm
- 7) Low Shore hardness
- 8) Good thermal shock resistance
- 9) Low dielectric constant
- 10) High temperature class
- 11) Low vacuum and thermal weight loss.

Although the scope of the program did not permit an exhaustive investigation of impregnating/encapsulating resins, a study was made of a number of resins including epoxies, polyurethanes, polyimides, and silicones. Many of these were eliminated from consideration for various reasons, such as high viscosity or high weight loss. Six materials were selected as exhibiting many of the desired properties. A comparative listing of properties of these materials is presented in Table 39.

A study of Table 39 will show that all of the compounds listed have low viscosity (under 1000 centipoise) in the working temperature range with the exception of 3M's No. 281. No. 281 has low weight loss and good thermal shock resistance, rendering it suitable as an encapsulant but not as an impregnant. No. 235 has high weight loss but could be considered as an impregnant if further encapsulated in a low weight loss compound. No. 280 has low viscosity, good thermal shock resistance, and moderate weight loss. No. 250 and No. 251 have outstandingly low weight loss, but No. 250 has poor thermal shock resistance. No. 2524 polyurethane is an elastomer of low viscosity, moderate weight loss, good thermal shock resistance, but short pot life.

The more promising of the compounds listed in Table 39, plus two additional polyurethanes were selected for the experimental program described in Section 5.4

A list of materials suitable for encapsulated transformers is given in Table 40. The vendors for these materials are listed in Appendix C.

TABLE 39
SOME PROPERTIES OF CANDIDATE RESINS FOR COIL IMPREGNATION

Manufacture Compound Number Class	3M #235 Unfilled Epoxy	3M #250 Unfilled Epoxy	3M #251 Filled Epoxy	3M #280 Unfilled Epoxy	3M #281 Filled Epoxy	Conap #2524 Unfilled Polyurethane
Weight Loss % in 1000 hrs. @ 130°C 7 days @ 130°C	4.4 ---	.01 ---	.01 ---	.51 ---	.17 ---	---- .26
Thermal Shock -55 to 130°C 1/8 Oliphant Washer	Pass	---	---	---	---	----
1/4 Oliphant Washer	Fail	---	---	Pass	Pass	----
MIL-1-16923E -55 to 105°C	---	Fail	Pass	---	---	----
-55 to 130°C	---	---	---	---	---	Pass
Viscosity (cps) 77°C, 1 hr.	160	70	160	130	1300	----
77°C, 2 hrs.	300	100	260	160	2000	----
77°C, 3 hrs.	850	200	800	400	3000	----
Rm. Temp. initial	1500	1800	19000	4000	48000	520
Rm. Temp. 1/2 hr	---	---	---	---	---	1200
Hardness Shore " Barcol	55D	25	40	70D	75D	70A
Shrinkage on Cure, Linear	-----Unknown-----					.90
Coeff. of Ex pansion/°C	16×10^{-5}	6.5×10^{-5}	3.0×10^{-5}	21×10^{-5}	15×10^{-5}	21×10^{-5}
Peak Exotherm	-----Unknown-----					70°C
Dielectric constant 25°C, 100 Hz	4.75	3.81	5.61	4.07	4.03	4.2
Temp. Class °C	130	155	155	155	155	130
Vendor's Minimum Cure Temp., °C	75	75	75	65	65	25

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TABLE 40
LIST OF MATERIALS FOR ENCAPSULATED TRANSFORMERS

Magnet Wire

Polyimide double coated, HML

Layer and Interwinding Insulation

Polyimide film, Kapton H, 2 mil, 5 mil

Polyester web, oriented, Pellon Corp. #7200, 1.2 mils

Aramid web, oriented, Pellon Corp. #2104, 2.8 mils

Structural Materials (Coil Forms, Panels)

Polyimide-Fiberglass Laminate, NEMA Grade G-30, 31 to 125 mils

Tying and Lacing Tape

Aramid, nylon treated, Gudebrod R&D #1141

Adhesive

Polyamide-imide, Rhodia Corp., Keramid #500

Polyimide, Upjohn #2080D

Conformal Coating

Polyimide, Upjohn #2080D

Lead Wire

Polyimide-fluorocarbon wrapped

Core Materials

Nickel-Iron-Molybdenum Alloy, 1-mil, Permalloy 80

Ferrite, Ceramic Magnetics MN-100

Heat Sink and Bonding Material

Filled silicone rubber compound, Dow Corning C6-1102

Silver filled epoxy

Impregnating and Encapsulating Compounds

Filled rigid epoxy, Scotchcast #251

Unfilled semi-rigid epoxy, Scotchcast #280

7.2 Voltage Stress Design Criteria For Encapsulated Transformers

Based on minimum CEV levels determined on specimen coils tested in the temperature range 25 to 100 degrees C, after aging at 100 degrees C, (Section 5, Table. 21) the design criteria given in Table 41 are considered conservative.

TABLE 41 Design Criteria for Voltage Stress in Encapsulated Transformers		
Insulation Thickness (Mils)	Voltage (Volts RMS)	Average Voltage Stress (Volts per Mil)
5	2500	500
10	3000	300
20	4500	225
30	6000	200

The values in Table 41 are for insulation consisting of interleaved layers of Kapton H polyimide film and Pellon non-woven oriented polyester web, impregnated with Scotchcast 251 epoxy.

Additional work is needed to establish criteria for higher voltages. At this time, a maximum stress of 100 volts per mil is recommended for voltages in the ranges 7000 to 10000 volts RMS. Creepage distances are the same as those recommended for open coils (Section 6, Table 24).

7.3 Design Calculations and Test Results For Encapsulated Transformer, EM-2, Sub 4.

The EM-2 transformer has the same requirements as the OM-2 (See Section 6.3) except that the EM-2 coil structure is encapsulated.

7.3.1 Calculation of $A_c A_w$ Product and Selection of Core

The same values for calculating the $A_c A_w$ product of the OM-2 Sub 6 transformer and given in Section 6.3.1 are used in equation (3.5) except that $B_m = 5.3\text{KG}$ and $(SF)_w = 0.25$. The calculated $A_c A_w$ product is $26.3 \text{ cm}^4 = 0.63 \text{ in}^4$.

The core selected was a Permalloy 80, 1 mil tape wound C-core, manufactured by Magnetics, Inc. (MC-1389-B). The D and E dimensions of this core are identical to those for the OM-2 Sub 6 and Sub 7 transformers. Core MC-1389-B has the following description:

Dimensions: D = 5/8 in; E = 5/8 in.
F = 3/4 in; G = 2 3/8 in.

A_c = Cross-sectional area	= DXE	= 0.39 in ²
A_w = Window area	= FXG	= 1.78 in ²
$A_c A_w$		= 0.70 in ⁴
Weight		= 0.75 lb

7.3.2 Calculation of Number of Turns, Wire Size

A two coil construction is used and the winding arrangement of each coil is the same. The primary windings on each coil are connected in **parallel** while both the secondary 1 and secondary 2 windings on each coil are series connected.

Primary

By equation (3.1) the number of primary turns is calculated to be 39. For a tube clearance of 1/8 in., the coil tube width is $2\frac{1}{4}$ in; the primary winding width is $1\frac{7}{8}$ in. for 1/16 in. flanges and 1/8 in. margins.

The maximum insulated wire diameter is $\frac{1.7/8}{39} = 0.0481$ in. which corresponds to #17 HML wire. The primary will consist of a single layer of 39 turns on each coil. The cross-sectional area of the bare #17 AWG wire is 2050 cir. mils. The primary current in each parallel winding is $\frac{13.3}{2} = 6.65$ A since the primary windings on each coil are in parallel. The primary inverse current density by equation (3.6) is

$$J_p = \frac{a_p}{I_p} = \frac{2050 \text{ cir. mils}}{6.65\text{A}} = 308 \text{ cir. mils/A}$$

Secondary 1

The number of secondary 1 turns is

$$N_{s1} = \frac{E_{s1}}{E_p} N_p = \frac{1100}{200} 39 = 215$$

The secondary 1 winding width is $1\frac{3}{4}$ in. for 1/16 in. flanges and 3/16 in. margins. Each coil is wound with 2 layers of #21 HML wire. One coil consists of 55 turns per layer while the other coil consists of 55 turns on one layer and 53 turns on the other. All four layers are series connected to give the required 215 turns.

The cross-sectional area of the bare #21 AWG wire is 812 cir. mils.

The secondary 1 current is 2.2A so the inverse current density is 369 cir. mils/A.

Secondary 2

The number of secondary 2 turns is

$$N_{S2} = \left(\frac{E_{S2}}{E_p} \right) N_p = \left(\frac{1000}{200} \right) (39) = 195$$

The secondary 2 winding width is $1\frac{1}{2}$ in. for 1/16 in. flanges and 5/16 in. margins. One coil is wound with 98 turns and the other with 97 turns and the coils are series connected. The wire size is #28 HML which has a bare cross-sectional area of 159 cir. mils. The secondary 2 current is 0.2A so the inverse current density is 795 cir. mils/A.

7.3.3 Layer and Interwinding Insulation, Coil Build, Window Space Factor

The description of the layer and interwinding insulation is given in Section 7.1.1. The coil build-up is given in Table 42. The window space factor, $(SF)_w$, is calculated according to the procedure given in Section 6.3.3 and $(SF)_w$ is 16%.

TABLE 42 COIL BUILD-UP FOR EACH COIL OF TRANSFORMER EM-2 SUB 4		
Build-Up Sequence	Incremental Build (in)	Total Build (in)
Tube Wall	0.055	0.055
Tube Wrapper (3 X 0.002 in)	0.006	0.061
Primary #17 HML	0.049	0.110
Primary Wrapper (2 X 0.0062 in)	0.012	0.122
Shield	0.002	0.124
Shield Wrapper (3 X 0.0062 in)	0.019	0.143
Sec. 1, Layer 1, #21 HML	0.031	0.174
Sec. 1, Layer 1 Wrapper (2 X 0.0062 in)	0.012	0.186
Sec. 1, Layer 2, #21 HML	0.031	0.217
Sec. 1, Layer 2 Wrapper (3 X 0.0062 in)	0.019	0.236
Sec. 2, #28 HML	0.015	0.251
Sec. 2 Wrapper (3 X 0.0062 in)	0.019	0.270

7.3.4 Calculation of Losses and Efficiency

Core Loss

The vendor's data gives the specific core loss as 22 watts/lb for a Permalloy 80, 1 mil, tape wound C-core under sinusoidal voltage excitation at 12 KHz and 5.3 KG. The core weighs 0.75 lb., so the core loss is 16.5 watts.

Conductor (I^2R) Loss

Equations (3.7) through (3.11) and the information given in Table 42 are used to calculate the I^2R loss for each winding. Table 43 gives the results. The inside dimensions of the coil tube are 21/32 in. X 23/32 in.

TABLE 43 Conductor (I^2R) Losses For Transformer EM-2 Sub 4			
	Primary	Secondary 1	Secondary 2
Average Number of Turns/Coil	39	107.5	97.5
MLT/Coil (in)	3.29	3.88	4.28
Winding Length/Coil (ft)	10.69	34.76	34.78
Wire Size (AWG)	#17	#21	#28
DC Resistance (ohms) per ft	0.00505	0.0128	0.0653
DC Resistance @ 20 °C (ohms)	0.0270(1)	0.890(2)	4.54(2)
Current (A)	13.3	2.2	0.2
I^2R loss @ 20 °C (watts)	4.78	4.31	0.18
Total I^2R Loss @ 20 °C = 4.78 + 4.31 + 0.18 = 9.3 watts			
(1) Two coils in parallel			
(2) Two coils in series			

Efficiency

The computed efficiency using equation (3.12) is

$$\eta = \frac{P_{out}}{P_{out} + P_T} \times 100 = \frac{(2620)(100)}{(2620 + 16.5 + 9.1)} = 99.0\% @ 20^\circ \text{C}$$

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7.3.5 Construction and Fabrication

The Impregnation/Encapsulation Process

The properties of most resins, both before and after curing, are to a considerable extent dependent on the conditions of processing. Viscosity, pot life, shrinkage during cure, and peak exotherm are time/temperature related. Elevated temperature has the desirable effect of reducing viscosity but has adverse effects on pot life, shrinkage and exotherm. Slow cure at the lowest feasible temperature minimizes both the shrinkage during the curing process and the further shrinkage that occurs upon cooling the hardened resin to room temperature, and also reduces the peak exotherm.

The coils should be substantially free of moisture and occluded gases before impregnation in order to minimize bubbling and foaming in the impregnation process. This is accomplished by oven drying overnight followed by treatment for several hours under vacuum of 2 Torr or less. The compound is introduced under vacuum to a level sufficient to cover the coil. The vacuum is then broken and the coil is allowed to soak in the resin for a period of time during which the resin slowly penetrates the interior of the coil. At this stage the impregnation process is dependent on the pressure differential between the inside and outside of the coil to provide the force necessary for the flow of fluid. It is therefore essential that all seams and bolt threads in the mold be hermetically sealed to prevent air from entering the mold assembly and reducing the pressure differential. Depending on the size and structure of the coil and the viscosity of the resin, it may be necessary to employ pressures higher than atmospheric in order to force the resin into the interstices of the coil. The time and temperature of the soak period are scheduled in accordance with the properties of the resin to allow impregnation to take place during a period within which the resin retains low viscosity, preferably under 1000 centipoise.

The curing process will vary with the nature of the resin, but should be carried out at a temperature that will permit the resin to harden, but not completely cure, over a period of 16 hours or longer. Following this, the unit may be removed from the mold and post-cured to develop optimum properties of the resin.

To summarize, a typical impregnation/encapsulation process will include the following steps:

1. Assemble the coil in the mold and coat all seams and bolts with a sealant such as rubber latex, room curing polyurethane, or silicone rubber compound.
2. Dry the coil and mold overnight at 110 degrees C.
3. Place in vacuum of 2 Torr or better for a minimum of 4 hours.
4. Introduce the mixed and degassed compound with the coil still under vacuum.
5. Soak the coil immersed in the fluid resin at atmospheric or higher pressure within a temperature range in which the resin exhibits low viscosity (less than 2000 centipoise) for a period of time sufficient to ensure thorough impregnation.
6. Cure slowly at the lowest feasible temperature consistent with the properties of the resin.
7. Remove coil from mold and post-cure in accordance with a suitable time/temperature scale to develop fully cured properties (e.g., hardness) of the resin.

Processing details utilizing specific resins are presented in Section 5.4.

Process For The Encapsulation Of Coils in Scotchcast 251

The specific procedure to be followed for impregnation and encapsulation in Scotchcast 251 is given in Table 44 (Process Specification MC-103).

TABLE 44

PROCESS SPECIFICATION MC-103

IMPREGNATION AND ENCAPSULATION OF PARTS IN SCOTCHCAST #251

I. PURPOSE

This specification covers the method of impregnating and encapsulating transformer windings in low weight loss filled epoxy for the purpose of minimizing corona and providing environmental protection.

II. EQUIPMENT

1. Forced convection oven with temperature control 60° to $125^{\circ}\text{C} \pm 2^{\circ}\text{C}$.
2. Vacuum chamber and accessory equipment capable of 2 Torr or better with provision for introducing epoxy into the chamber while maintaining the vacuum.

III. MATERIALS

1. Room temperature cure polyurethane compound, Conap EN-2523, parts A and B.
2. Scotchcast #251, 3M Company

IV. PROCEDURE

1. Assemble coil in the mold, coating the seams of the mold with Conap EN-2523 mixed in the ratio 1 part A to 5 parts B by weight. Let stand 2 hours minimum at room temperature to gel the sealant.
2. Dry the coils assembled in molds, 16 hours minimum at 110 degrees C.
3. Place molds in vacuum chamber with tube properly arranged for introduction of the compound and evacuate at 2 Torr for 4 hours minimum at room temperature.
4. Preheat Scotchcast #251, parts A and B in original containers to 70 ± 10 degrees C. Stir each part thoroughly while hot to disperse the filler.
5. One hour before completion of the vacuum cycle of Paragraph 3, weigh out equal quantities of parts A and B in separate containers. Place in separate vacuum chamber and evacuate to 2 - 4 Torr until bubbling subsides. Return parts A and B to oven, heat to $60 - 70^{\circ}\text{C}$, and mix the two parts thoroughly in one container. Warm again to $60 - 70^{\circ}\text{C}$ and evacuate at 2 - 4 Torr until bubbling ceases. Return mixture to oven and warm to $50 - 60^{\circ}\text{C}$.

NOTE: After mixing parts A and B, evacuation and reheating should be accomplished in 1/2 hour or less.

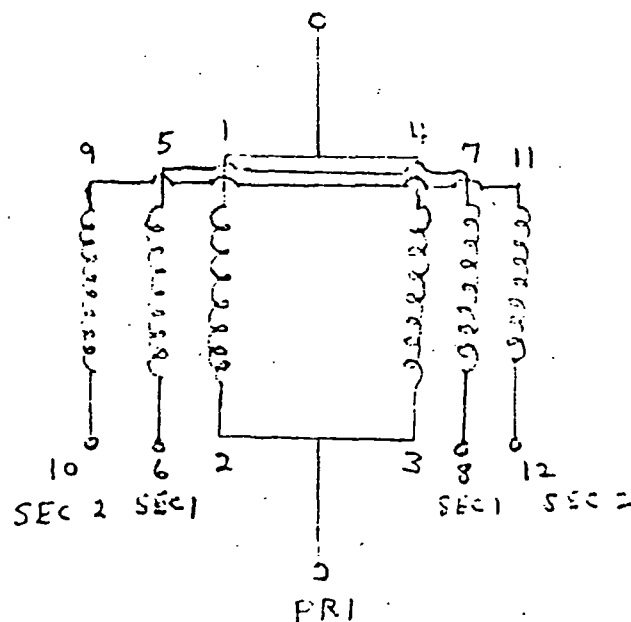
PROCESS SPECIFICATION ON MC-103 (Continued)

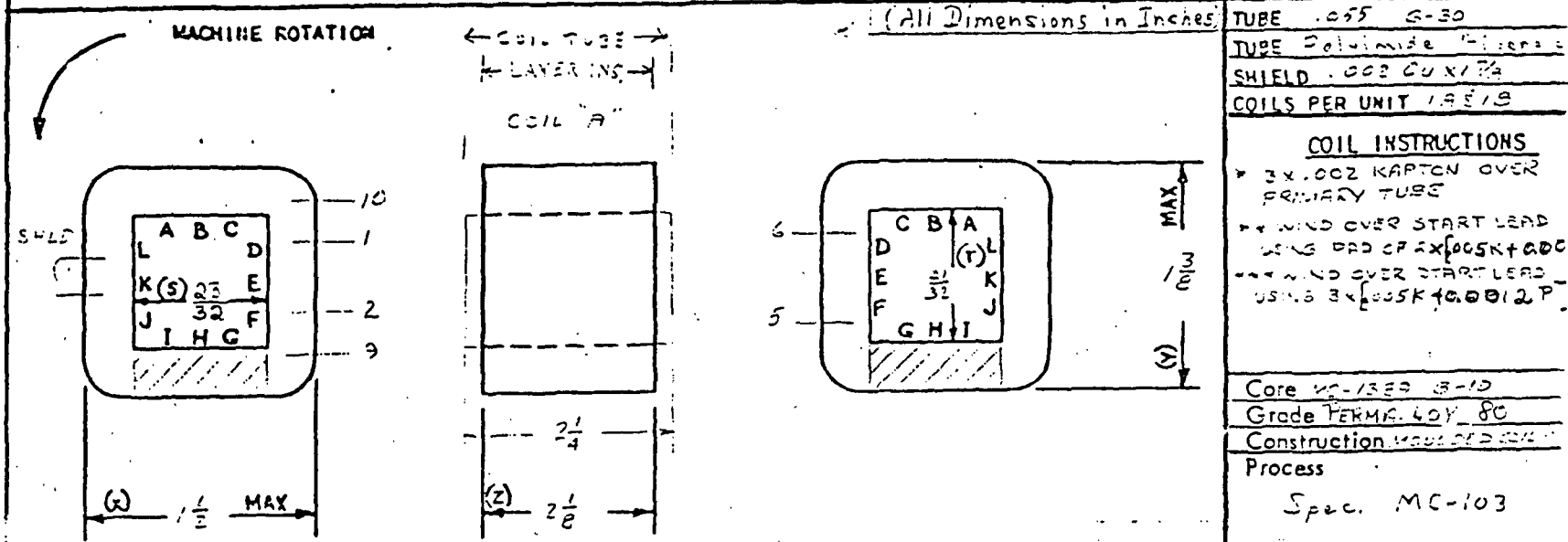
6. After completion of the vacuum cycle (Paragraph 3), introduce the warm compound into the mold slowly while maintaining vacuum of 2 Torr. Admit the compound at such a rate as to prevent excessive foaming.
7. When the mold is about 3/4 full, close off the inlet tube and maintain vacuum for 5 - 10 minutes until major bubbling subsides.
8. Continue admission of compound until the mold is full.
9. Shut off inlet tube and continue vacuum for 5 - 10 minutes.
10. Shut off vacuum pump and admit air slowly during a period of 5 - 10 minutes until the pressure in the chamber is atmospheric.
11. Remove mold from the chamber and if necessary top off with warm compound (50 - 60 degrees C).
12. Place in oven at 68 ± 2 degrees C and cure 16 hours at this temperature.
13. Post cure 4 hours at 75 ± 2 degrees C.
14. Remove the coil from the mold.
15. Post-cure 16 hours at $100 \pm 5 - 0$ degrees C.

7.3.6 Manufacturing Specification Sheets

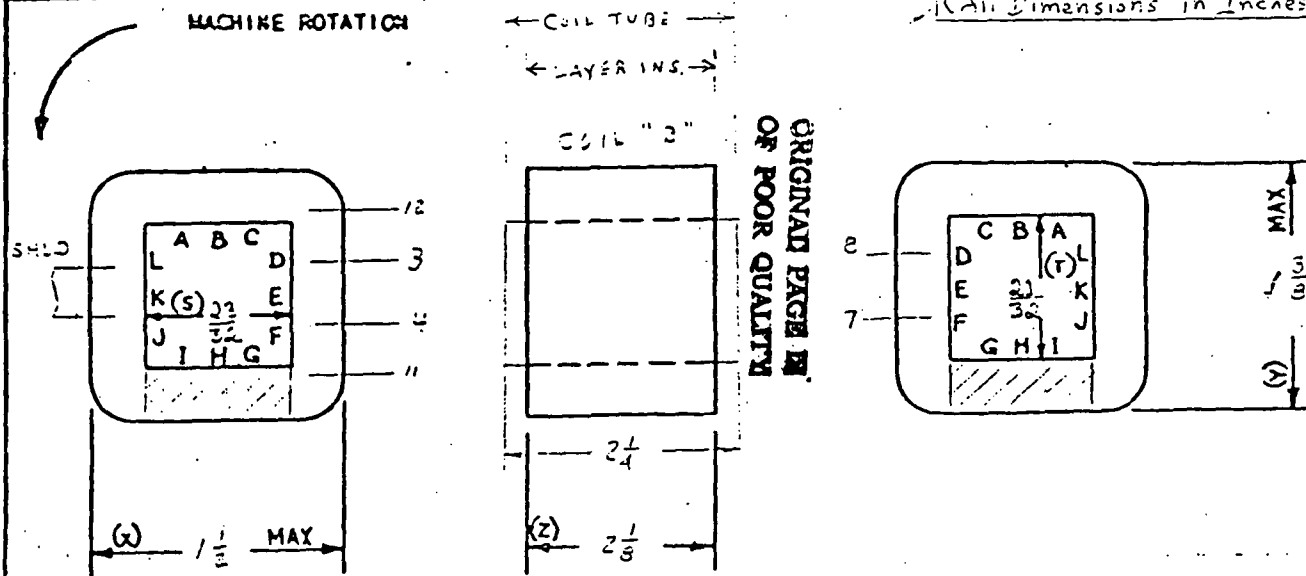
The schematic, coil lay-out, and outline drawings for transformer EM-2 Sub 4 are as follows:

SCHEMATIC: EM-2 Sub 4



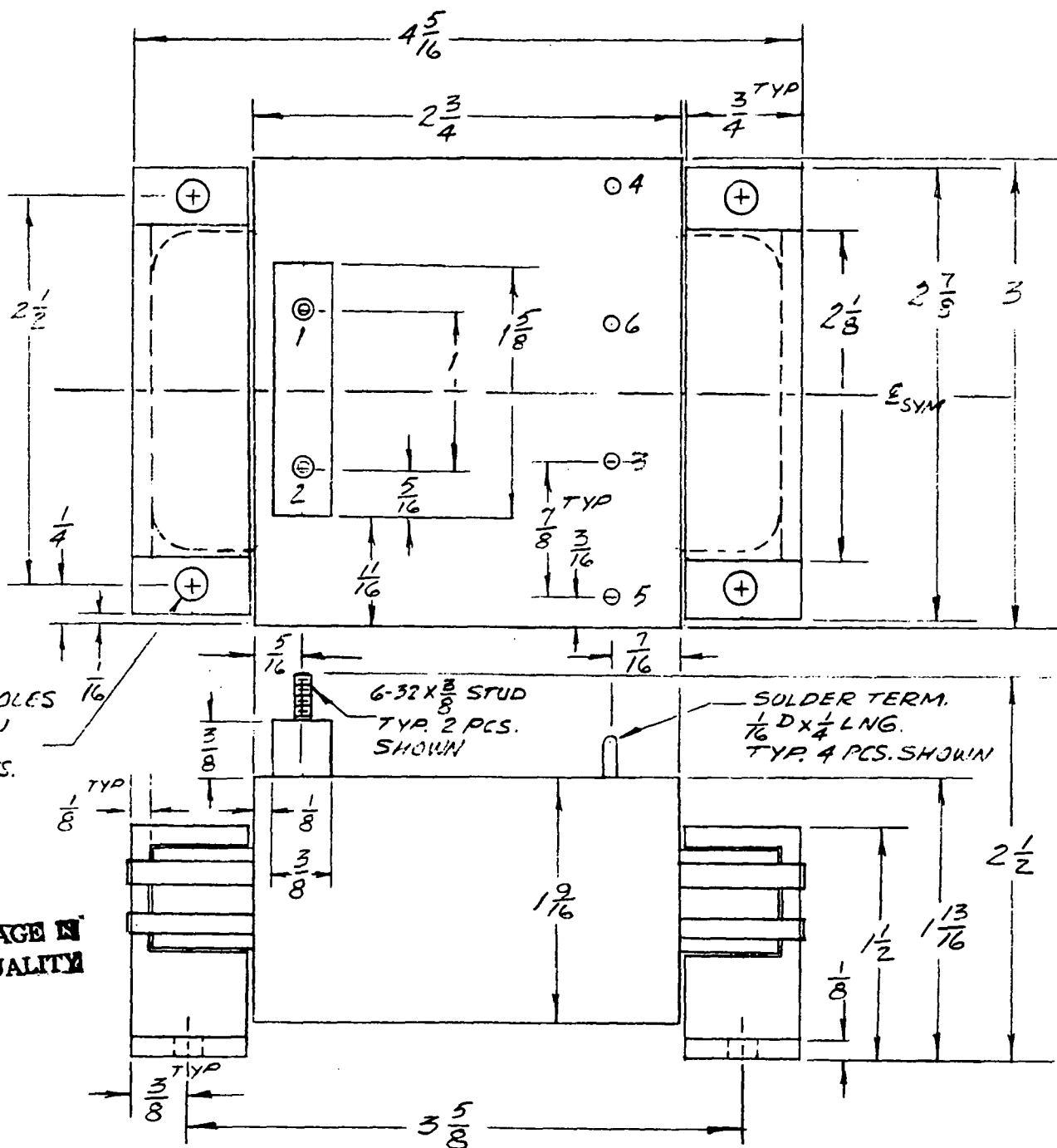


WINDING NO.	1-2	5-6	9-10			Input Voltage	200V
URNS	39	108	98			Frequency	12 KHz
URNS AT TAP	---	---	---			Type Of Primary	
WIRE SIZE	#17 NML	#21 NML	#28 NML			No. of Secondaries	2
WINDING WIDTH	1 3/8	1 3/8	1 1/2			Voltage Across Each Secondary	#1 1.1 KV #2 1.0 KV
MARGIN	1/8	5/16	5/16			Total Output Voltage	
URNS / LAYERS	39 / 1	54 / 2	98 / 1			Total Output Power	2.62 KVA
LAYER INSUL.	---	2x (.005K + .002P)	---			Maximum Mass	2K9
WIND ON OR OVER	TUBE	SH-WRAP	5-6 WRAP			B max	5.3 KG
LEAD WIRE	SELF	SELF	SELF			Core Loss	16.5 W
LEAD LENGTH	6"	6"	6"			Efficiency	99.0% @ 20°C
LEAD INSULATION	---	---	---			Weight	879 gm
COIL WRAPPER	2x (.005K + .002P)	3x (.005K + .002P)	3x (.005K + .002P)				
SHIELD WRAPPER	3x (.005K + .002P)	---	---				
SHIELD LEAD	CU TIE	---	---				
D.C. RESISTANCE	0.054Ω	0.445Ω	2.27Ω				
WT. OF WIRE	0.76#	0.089#	0.017#				



WINDING NO.	3-4	7-8	11-12			Input Voltage	200 V
TURNS	39	107	97			Frequency	15 KHZ
TURNS AT TAP	---	---	---			Type Of Primary	
WIRE SIZE	#17 AWG	#21 AWG	#28 AWG			No. of Secondaries	2
WINDING WIDTH	1 3/8	1 3/4	1 1/2			Voltage Across	#1 1.1 KW
MARGIN	1/8	3/16	5/16			Each Secondary	#2 1.0 KW
TURNS/LAYERS	39/1	54/1 53/1	97/1			Total Output Voltage	
LAYER INSUL.	---	2X[0.005K 0.0012P]	---			Total Output Power	2.62 KVA
WIND COIL OR OVER	TUBE	SH-WRAP	2-3 WEEP			Maximum Mass	1 KG
LEAD WIRE	SELF	SELF	SELF			Bmax	5.3 KG
LEAD LENGTH	6"	6"	6"			Core Loss	16.5 W
LEAD INSULATION	---	---	---			Efficiency	99.0% @ 20°C
COIL WRAPPER	2X[0.005K +0.0012P]	3X[0.005K +0.0012P]	3X[0.005K +0.0012P]			Weight	879 g/m
SHIELD WRAPPER	3X[0.005K +0.0012P]	---	---				
SHIELD LEAD	CU TAP	---	---				
D.C. RESISTANCE	0.05-Ω	0.445Ω	2.27Ω				
WT. OF WIRE	0.068#	0.088#	0.017#				

APPLICATION			REVISIONS		
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED



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UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES

TOLERANCES: ANGLES $\pm$ ~

FRACTIONS $\pm \frac{1}{64}$

3 PLACE DECIMALS $\pm$ ~

2 PLACE DECIMALS $\pm$ ~

1 PLACE DECIMALS $\pm$ ~

MATERIAL:

CONTR NO.

NAS 3-177E1

DR

RFC

12/15/76

CHK

A

P

D

APPROVED

BY DIRECTION OF



MAGCAP ENGINEERING INC.

222 BOLIVAR STREET CANTON, MASS.

DRAWING TITLE

EM-2 OUTLINE
SUB 4

SIZE

A

CODE IDENT NO.

DRAWING NO.

SCALE FULL

SHEET

2 OF 5

7.3.7 Corona Test Results

The EM-2 Sub 4 transformer was built in accordance with Section 7.3.5 and Section 7.3.6. The corona test results are given in Table 45. These test results indicate that the EM-2 Sub 4 transformer should be 'corona free' at the required operating voltages.

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TABLE 45 CORONA TESTS ON EM-2 TRANSFORMER	
Points Of Test	CIV/CEV (KV RMS)
Secondary 1 - Primary	3.2/3.1
Seconary 2 - Primary	5.3/4.0
Secondary 1 - Secondary 2	3.5/3.4
Secondary 1 - Primary and Shield	1.5/1.4
Secondary 2 - Primary and Shield	3.1/2.7
Secondary 1 - Shield only	1.5/1.3
Secondary 2 - Shield only	3.1/2.7

7.4 Design Calculations and Test Results for Encapsulated Transformer ES-10 Sub 3

The requirements of the ES-10 transformer are as follows:

Primary Voltage	60 V
Type of Primary	Center-Tapped
Secondary Voltage	10 kV
Output Power	500 VA
Input Waveform	Square Wave
Frequency Limits	2-40 kHz
Efficiency	97% Minimum
Ambient Temperature Range	-55 to 85° C
Weight	1.25 kg max.
Construction	Encapsulated

7.4.1 Core Description

The core selected was a Permalloy 80, 1 mil, tape wound C-core, manufactured by Magnetics, Inc. (MC-1610). This core has the following description:

Dimensions: D = 1/2 in.; E = 1/2 in.

F = 1-1/2 in.; G = 1-1/2 in.

A_C = Cross-sectional area = $D \times E = 1.61 \text{ cm}^2 = 0.25 \text{ in}^2$

A_W = Window Area = $F \times G = 2.25 \text{ in}^2$

$A_C A_W = 0.56 \text{ in}^4$

$(SF)_C$ = Space factor of core = 0.8

Weight = 0.5 lb

7.4.2 Calculation of Number of Turns, Wire Size

A single coil construction is used with the primary placed first on the coil tube.

Primary

The primary is bifilar wound and two ends of the winding are tied together to form the center tap. Each tap has the same number of turns. The operating frequency is 12 kHz and the maximum flux density is 3.87 KG. Each tap has 25 turns which is calculated by equation (3.1) and the information given in the requirements and core description above.

The coil tube width is $1-7/16$ in. for a $1/16$ in. tube clearance. For $1/16$ in. flanges and $9/64$ in. margins, the primary winding width is $1-1/32$ in. For this width and 25 turns, the maximum insulated wire diameter is 0.0413 in. This corresponds to #19 HML wire which has a bare wire cross-sectional area of 1290 cir. mils. The primary consists of two layers; one of 13 turns, the other of 12 turns. If the input power is assumed to be approximately equal to the output power of 500 VA, and for 60 V impressed across each tapped winding, the current is 8.34 A and the inverse current density is 155 cir. mils/A. Each tapped winding has a 50% duty cycle.

Secondary

For a secondary output voltage of 10 kV, input primary voltage of 60 V, and 25 primary turns, the required number of secondary turns is 4170. The secondary winding width is $7/8$ in. for $7/32$

margins. The wire size selected is #34 HML and 41 layers of 100 turns and 1 layer of 70 turns is required. The secondary current is 0.05 A and since the bare cross-sectional area of the #34 wire is 39.7 cir. mils, then the inverse current density is 794 cir. mils/A.

7.4.3 Layer and Interwinding Insulation, Coil Build, Window Space Factor

The layer and interwinding insulation is described in Section 7.1.1. The coil-build up is given in Table 46. A window space factor, $(SF)_W$, of 0.08 is calculated for this transformer.

TABLE 46
COIL-BUILD UP FOR TRANSFORMER ES-10 SUB 3

Buildup Sequence	Incremental Build (in.)	Total Build (in.)
Tube Wall	0.055	0.055
Tube Wrapper (6x0.002 in.)	0.012	0.067
Primary, Layer 1, 2x#19 HML	0.391	0.106
Pri., Layer 1 Wrapper (2x0.005 in. + 0.0012 in.)	0.0112	0.117
Primary, Layer 2, 2x#19 HML	0.391	0.156
Primary, Layer 2 Wrapper (3x0.0062 in.)	0.0186	0.175
Shield	0.002	0.177
Shield Wrapper (13x0.0062 in.)	0.0806	0.258
Secondary: 42 layers of #34 HML and 42 layers of (0.0062 in.)	0.8484 ⁽¹⁾	1.106
Secondary Wrapper (6x0.0062 in.)	0.0372	1.143
(1) This includes an overlap of thickness 0.0062 in. for each of the 42 layers of insulation.		

7.4.4 Calculation of Losses and Efficiency

Core Loss

For sinusoidal voltage excitation at 12 kHz and 3.87 KG, the vendor's data gives the specific core loss as 12.7 watts/lb for a Permalloy 80, 1 mil, tape wound C-core. The core weight is 0.5 lbs, so the core loss is 6.4 watts.

Conductor (I^2R) Loss

Table 46 along with equations (3.7) through (3.11) are used to calculate the results given in Table 47. The inside dimensions of the core tube are 17/32 in. x 17/32 in.

TABLE 47
CONDUCTOR (I^2R) LOSSES FOR TRANSFORMER ES-10 SUB 3

	Primary	Secondary
Number of Turns	25	4170
MLT (in.)	2.83	6.41
Winding Length (ft)	5.90	2227
Wire Size (AWG)	#19	#34
DC Resistance (ohms) per ft	0.00805	0.261
DC Resistance @ 20° C (ohms)	0.047 ⁽¹⁾	581
Current (A)	8.34	0.05
I^2R loss @ 20° C (watts)	3.27 ⁽²⁾	1.45
Total I^2R loss = 3.27 + 1.45 = 4.7 watts		
(1) Resistance of each tapped winding		
(2) Total loss of primary for 50% duty cycle of each tapped winding		

Efficiency

The computed efficiency using equation (3.12) is 97.8% at 20° C.

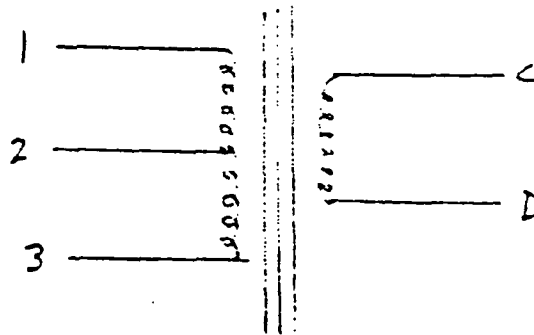
7.4.5 Construction and Fabrication

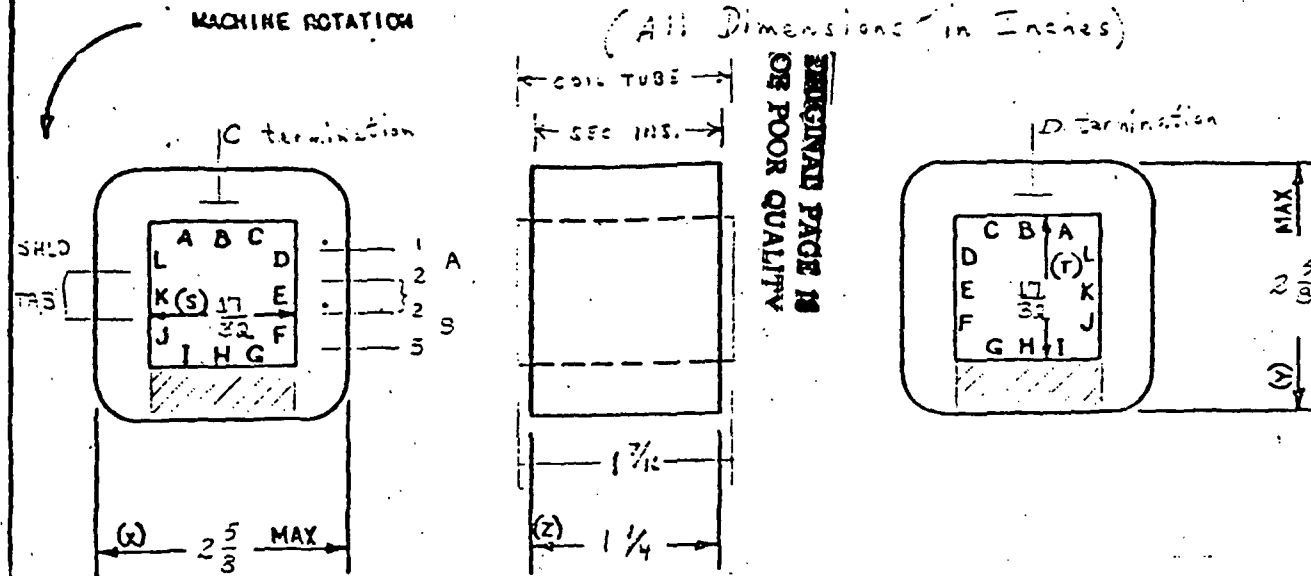
The coil of the OS-10 Sub 3 transformer is encapsulated according to the procedures given in Section 7.3.5.

7.4.6 Manufacturing Specification Sheets

The schematic, coil layout, and outline drawings for transformer OS-10 Sub 3 are as follows:

Schematic: ES-10 Sub 3





TUBE .055 G-30
TUBE Polyimide Finerolase
SHIELD 0.002 Cu
COILS PER UNIT 1

COIL INSTRUCTIONS

* 1X.000 KAPTON OVER
PRIMARY TUBE
** A BIFILAR WINDING

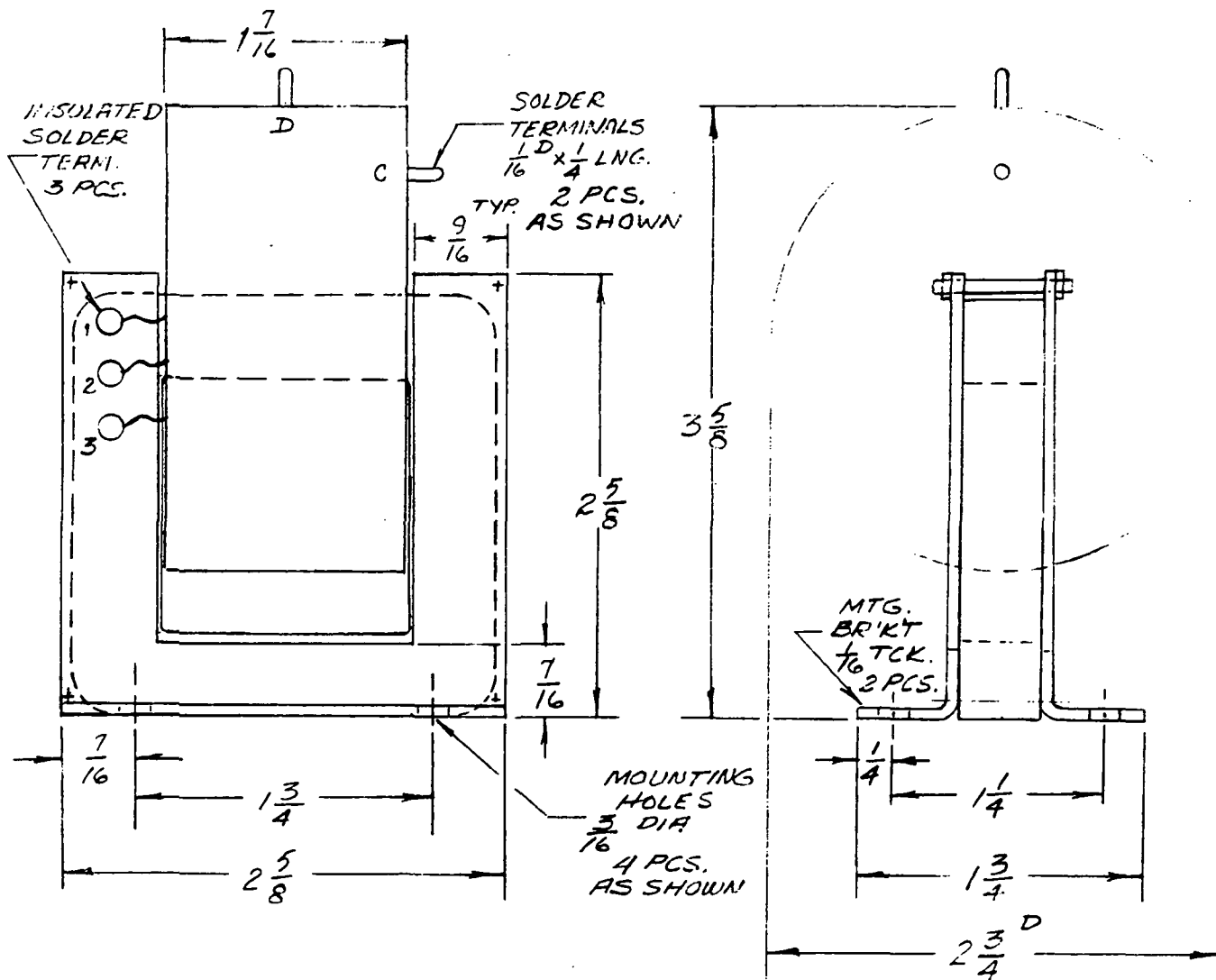
Core	MC-1610
Grade	PERMALLOY 40
Construction	MOULDED CC
Process	

MC - 103

WINDING NO.	A-B	C-D				Input Voltage	60V
TURNS	25	4170				Frequency	12 KHZ
TURNS AT TAP	--	---				Type Of Primary	CENTER-TAPPED
WIRE SIZE	2x #19 HML TM	#34 HML				No. of Secondaries	1
WINDING WIDTH	1 1/32	7/8				Voltage Across Each Secondary	10KV
MARGIN	7/32	1/4				Total Output Voltage	10KV
TURNS / LAYERS	13/1; 12/1	100/41; 70/1				Total Output Power	500VA
LAYER INSUL.	0.005K+0.0012P	0.005K+0.0012P				Maximum Mass	1.25KG
WIND ON OR OVER	TUBES	SH-WRAP				Bmax	3.97 KG
LEAD WIRE	SELF	SELF				Core Loss	6.4W
LEAD LENGTH	3"	6"				Efficiency	97.87, @20°C
LEAD INSULATION	--	--				Weight	
COIL WRAPPER	3x[0.005K +0.0012P]	6x[0.005K +0.0012P]					
SHIELD WRAPPER	13x[0.005K +0.0012]	---					
SHIELD LEAD	CU-TAP						
D.C. RESISTANCE	0.047Ω	521Ω					
WT. OF WIRE	0.047#	0.293#					

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UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		CONTR NO. <i>NAS 3-17161</i>		 MAGCAP ENGINEERING INC. 222 BOLIVAR STREET CANTON, MASS.	
TOLERANCES: ANGLES $\pm$		DR <i>LFC</i>	DATE <i>12-18-61</i>		
FRACTIONS $\pm$		CHK		DRAWING TITLE	
3 PLACE DECIMALS $\pm$		A		<i>ES-10 OUTLINE SUB 3</i>	
2 PLACE DECIMALS $\pm$		P			
1 PLACE DECIMALS $\pm$		D			
MATERIAL:		APPROVED		SIZE	CODE IDENT NO.
		BY DIRECTION OF		A	
				SCALE <i>FULL</i>	SHEET

7.4.7 Corona Test Results

The OS-10 Sub 3 transformer was built in accordance with Sections 7.4.5 and 7.4.6. The test results are given in Table 48. In Table 48 it is noted that the CIV/CEV levels improved on aging and that the CIV level at 70° C is higher than the room temperature level. There was evidence of air leakage into the mold due to imperfect sealing of one of the terminal pins. This could have been a cause of low CIV.

From the results in Table 48, it is noted that the CIV levels are lower than the secondary rated output of 10 kV. Under the conditions of the test, in which secondary and primary are each shorted, the test voltage appears on the entire secondary, including the first secondary layer. This does not represent the conditions of actual operation, in which only a fraction of the output voltage occurs on the first secondary layer.

The tests show that Layer 1 of the secondary is corona free to at least 5000 volts which is higher than the voltage it sees under operating conditions. There is therefore a good possibility that the transformer will operate corona free under operating conditions, since the outside layer which sees the full output voltage is removed from the first layer by several layers of additional insulation.

These considerations point to the need for a corona test method that will duplicate the operating conditions of the transformer.

TABLE 48 CORONA TESTS ON ES-10 - FIRST MOLDED UNIT SINGLE COIL CONSTRUCTION			
Points Of Test	CIV/CEV (Volts RMS)		
	3/20/75 Rm. Temp.	4/9/75 Rm. Temp.	4/9/75 70°C
Secondary to Primary & Shield	2800/1900	4000/3700	6100/5900
Secondary to Primary	5000/4600	6800/6700	6900/6800
Secondary to Shield	1600/1600	3600/3500	5900/5800
Primary to Shield	900/600	2000/1900	2200/2100

8.0 Comparison of Transformer Designs OM-2 Sub 6 and EM-2 Sub 4

A comparison of some of the characteristics of the OM-2 Sub 6 open-coil transformer and the EM-2 Sub 4 encapsulated-coil transformer are given in Table 49. The electrical requirements are the same for both transformers. Section 6.3 gives a detailed discussion of OM-2 Sub 6, while Section 7.3 gives a detailed discussion of EM-2 Sub 4.

TABLE 49
COMPARISON OF TRANSFORMERS OM-2 SUB 6 AND EM-2 SUB 7

Design	OM-2 Sub 6	EM-2 Sub 4
Core Material	Permalloy 80	Permalloy 80
Core Weight	1 lb	0.75 lb
Frequency	12 kHz	12 kHz
Maximum flux density	5 KG	5.3 KG
Core loss @ 20° C	18 watts	16.5 watts
I^2R loss @ 20° C	8.3 watts	9.3 watts
Total loss @ 20° C	26.3 watts	25.8 watts
Efficiency @ 20° C	99.0 %	99.0%
Temperature rise	60° C	Not calculated
Weight	964 gm (2.13 lb)	879 gm (1.94 gm)

From Table 49 it is seen that the losses and efficiency of the two transformers are comparable. It is anticipated that the temperature rise of the encapsulated transformer, although not calculated, would be somewhat lower due to the higher thermal conductivity of the encapsulated coil. The EM-2 Sub 4 transformer weighs 85 gms (0.19 lb)

less than the OM-2 Sub 6. This weight difference is mainly due to the difference in core weights (i.e., a difference of 0.25 lb). Thus, any increase in weight due to encapsulation in the EM-2 Sub 4 transformer is more than offset by the use of a lighter core.

APPENDIX A - REFERENCES CITED IN THE TEXT

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APPENDIX C - LIST OF VENDORS AND TRADE NAMES

POLYIMIDE INSULATED MAGNET WIRE

Anaconda Wire and Cable Co. (ML)
Belden Corp. (ML)
Essex International (Allen)
General Cable Corp. (Gen. ML)
Hudson Wire Co. (ML)
Phelps Dodge Magnet Wire Corp. (ML)
Rea Magnet Wire Co. (Pyre ML)
Viking Wire Co. (ML).

POLYIMIDE FIBER (KAPTON H)

E. I. DuPont de Nemours & Co., Inc.,
Film Dept., Wilmington, Del. 19898

ARAMID (POLYAMIDE) PAPER (NOMEX 410 Calendered; NOMEX 411 Uncalendered)

E. I. DuPont de Nemours & Co., Inc.
Textile Fibers Dept., Wilmington, Del. 19898.

MICA-FIBERGLASS LAMINATE (ISOMICA 4350)

U. S. Samica Corp., Rutland, Vt.

POLYESTER NON-WOVEN WEB (PELLON 7200)

Pellon Corporation, Industrial Division
221 Jackson Street, Lowell, Mass. 01852

ARAMID (NOMEX) POLYAMIDE NON-WOVEN WEB

Pellon Corporation, Industrial Division
221 Jackson Street, Lowell, Mass. 01852

FILLED EPOXY COMPOUND (SCOTCHCAST 251)

3M Company, 935 Bush Avenue, Box 3211,
St. Paul, Minn. 55101

POLYURETHENE ENCAPSULATING COMPOUNDS (CONATHANE EM-2524, EM-2522)

Conap Inc., Allegany, New York 14706.

SILICONE TREATED WOVEN FIBERGLASS LAMINATE, NEMA GRADE G-7

General Electric Company, Laminated Products Dept.,
Conshocton, Ohio 43812.

POLYIMIDE TREATED WOVEN FIBERGLASS LAMINATE (NEMA G-30)

UOP Norplex Division, LaCrosse, Wisconsin 54601.

APPENDIX C - LIST OF VENDORS AND TRADE NAMES

POLYAMIDE FIBER LACING TAPE (NOMEX LACING TAPE, STYLES R&D 1127, R&D 1121)

Gudebrod Bros. Silk Co., Inc.
12 South 12th Street, Philadelphia, Pa. 19107.

SILICONE RESIN (DOW CORNING 2104)

Dow Corning Corp., Midland, Michigan 48640.

POLYAMIDE-IMIDE ADHESIVE (KERIMID 500)

Rhodia, Inc., 600 Madison Avenue, New York, N.Y. 10022.

POLYIMIDE ADHESIVE (2080D)

Upjohn Polymer Chemicals, Box 685, LaPorte, Texas 77571.

LEAD WIRE - POLYIMIDE FILM WRAPPED

Harbor Industries Inc., Wire Division, Shelburne, Vt. 05482.

Technical Bulletin H-110C from
E. I. DuPont de Nemours & Co., Electrical Insulation Products Div.,
20 Evergreen Place, East Orange, New Jersey 07018.

PERMALLOY 80 CORE MATERIAL

Magnetics, Division of Spang Industries Components Division,
Butler, Pa. 16001.

FERRITE MN-100 CORE MATERIAL

Ceramic Magnetics Inc.
87 Fairfield Road, Fairfield, New Jersey 07006.

HEAT CONDUCTING COMPOUND (SILICONE 66-1102, SYLGARD 183)

Dow Corning Corporation, Midland, Michigan 48640.

APPENDIX D - TEST METHODS

D-1 MEASUREMENT OF CORONA INCEPTION/CORONA

EXTINCTION VOLTAGES

D-1-1 Equipment

Corona test set, 40 KV, 1 KVA RMS.

Square Wave Generator, output impedance not more than 100 ohms, rise time .1 usec or less, decay time to half crest greater than 1 millisecond.

Capacitance Bridge.

D-1-2 Calibration of the Corona Detector (Reference 11)

The output of the square wave generator is connected in series with the specimen to be tested on the high voltage side of the corona detector with the ground side of the generator connected to ground on the detector. (See circuit diagram, Figure 19). The specimen to be tested is first measured for capacitance. With the high voltage turned off, square wave voltages of .1 to .5 volts are introduced into the circuit and the deflection on the oscilloscope of the corona detector is measured in inches or centimeters. Volts per inch (or cm) of deflection is calculated and upon multiplying by the capacitance of the specimen in picofarads, the sensitivity of the corona detector is obtained in terms of picocoulombs per inch (or per cm).

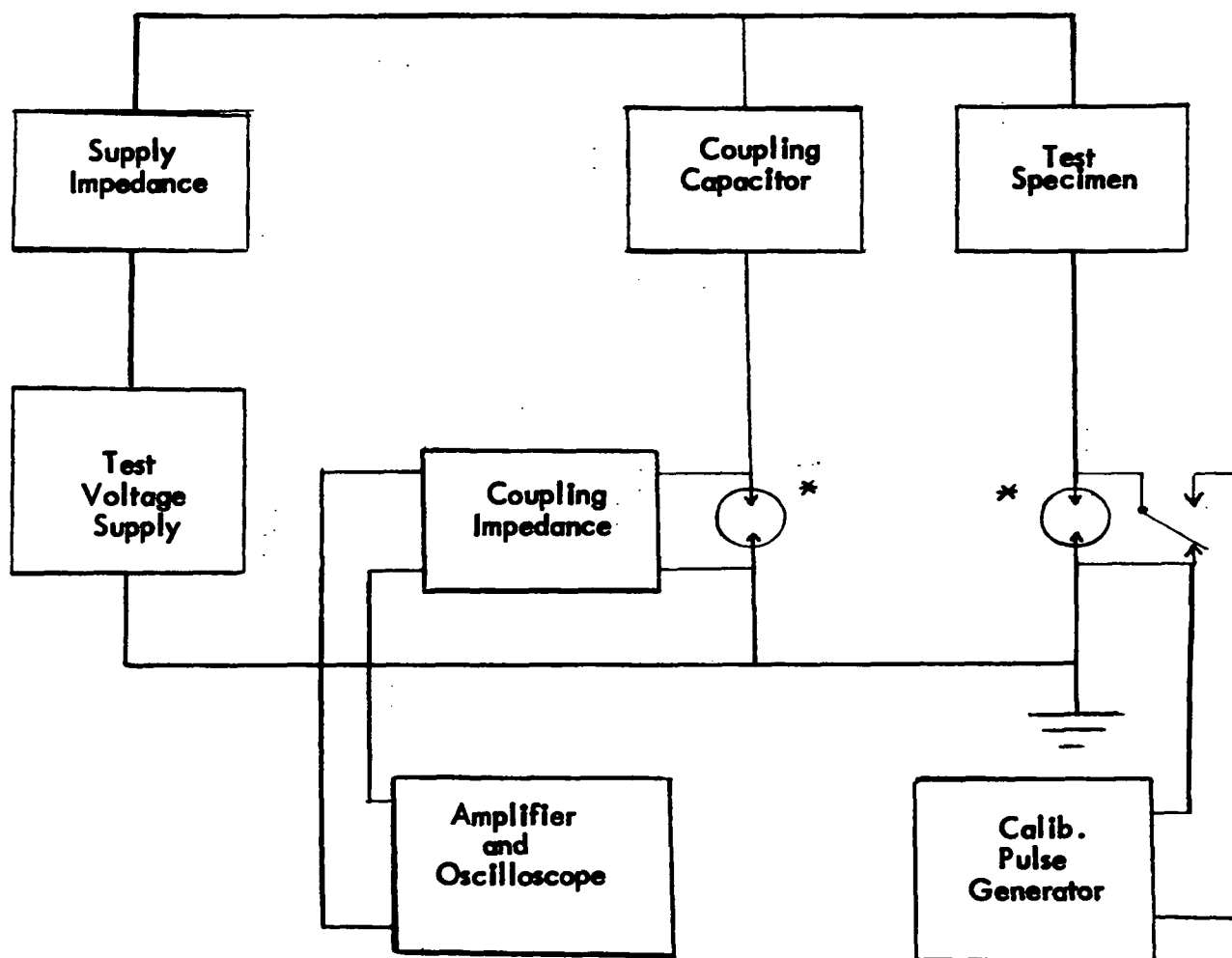
D-1-3 Measurement of CIV Level

Before connecting the unit to be tested to the high voltage terminals of the corona tester, the voltage is raised to the maximum value of the test and the oscilloscope screen is viewed to assure the absence of corona associated with the equipment.

In performing tests on transformers, all windings are shorted and corona tests are made between windings and between core and shield (if any) and windings. The voltage is advanced slowly until recurrent corona pulses first appear on the oscilloscope.

The voltage at which this occurs is recorded as the corona inception voltage. The voltage is then slowly reduced until all pulses disappear from the scope and this point is recorded as the corona extinction voltage.

Repetitive corona measurements on the same winding should be kept to a minimum to prevent degradation of the insulation.



* Surge Protector (Optional)

FIGURE 19 - Circuit For Corona Measurement Including Calibration Equipment
(Reference: ASTM D1868-73, Figure 1)